EFFECTS OF THE HEAD OF OLD RIVER BARRIER ON FLOW AND WATER QUALITY IN THE SAN JOAQUIN RIVER AND STOCKTON DEEP WATER SHIP CHANNEL

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Acronyms and Abbreviations

µS/cm	microsiemens/centimeters
BDT	Brandt Bridge Station
BODs	biochemical oxygen demands
cBOD	carbonaceous BOD
cfs	cubic feet per second
CVP	Central Valley Project
DO	dissolved oxygen
DWR	California Department of Water Resources
DWSC	Deep Water Ship Channel
EC	electrical conductivity
EWA	Environmental Water Account
g/L	grams per liter
HOR	Head of Old River
HORB	Head of Old River Barrier
lb/d	pounds per day
mg/L	milligrams per liter
MGD	million gallons per day
mL	milliliters
OP	Outfall Pier
PAR	photosynthetically available radiation
Pforb	Pseudodiaptomus forbesi
RM	river mile
RRI	Rough and Ready Island
SBC	Stockton Brick Company
SJG	San Joaquin River Garwood
SJR	San Joaquin River
SWP	State Water Project
USGS	U.S. Geologic Survey
UV	ultraviolet
mm	micrometer

Overview

Longitudinal water quality monitoring was performed on the San Joaquin River (SJR) from Mossdale Crossing to Turner Cut to assess the benefit of installing the head of Old River barrier (HORB). The installation of the HORB is performed by the California Department of Water Resources (DWR) in conjunction with additional reservoir releases to increase flow and dissolved oxygen (DO) concentrations in the Stockton Deep Water Ship Channel (DWSC) for migrating fall Chinook salmon. These management practices can temporarily benefit DO, but low DO concentrations may reappear after the removal of the HORB and the reduction of reservoir releases. A recent notable case occurred in 2002 after DO concentrations were raised from below 3 milligrams per liter (mg/L) to levels exceeding 9 mg/L at the DWR Rough and Ready Island (RRI) monitoring station. After the HORB removal and the reduction of pulse flows, DO concentrations fell below 3 mg/L.

The response of the DO in the DWSC is complex and may be difficult to predict solely by flow management. Other factors, such as concentrations of oxygen-demanding substances or temperature also influence DO concentrations. Since 2000, DO levels in the DWSC have been observed to increase about 2 to 3 mg/L with the placement of the HORB and pulse flows generated by reservoir releases.

This study was designed to evaluate the influence of the HORB on water quality and biological characteristics of the SJR flows as they enter the DWSC. The response of the DWSC flows and water quality after the removal of the HORB were also evaluated. Results from this study may improve operational management of the DWR aeration facility by enhancing the understanding of the DO response in the DWSC to changes in SJR flow and quality.

Study Elements

This study was accomplished by completing the following steps:

1. Develop the relationship between flow and travel time from the HORB to the DWSC using dye studies.
2. Assess water quality impacts with longitudinal monitoring conducted before, during, and after the installation of the HORB. Measurement of DO, oxygen-demanding substances (e.g., ammonia and algae, and biochemical oxygen demands [BODs], tests) and zooplankton (algae grazers) were emphasized.
3. Analyze water quality data for important correlations and calculate loads of oxygen-demanding substances.

Answers to Study Questions

1. **What is the effect of installing the HORB on downstream flow and travel time?**

Four dye releases were used to develop the relationship between net flow to the DWSC and travel time from the HORB to the DWSC. The net flow estimated by the observed dye travel time proved to be consistent with net flows calculated from tidal flow measurements recorded at the San Joaquin River Garwood (SJG) station.

Net flows from SJG and Vernalis are presented in Figure 6 for the study period. Vernalis flows represent the total flow entering the San Joaquin River Delta. At the Head of Old River (HOR) the flow splits with most water traveling down Old River, away from the Stockton DWSC, and toward the South Delta Pumping stations (see Figure 1). Prior to the installation of the HORB in 2007, approximately 30 to 40% of the flow remained in the San Joaquin River and flowed to the DWSC. With the HORB in place, 70 to 80% of the flow passed through the DWSC (see Figure 7). The other 20 to 30% was diverted to Old River to maintain water quality and provide dilution of the City of Tracy's wastewater effluent. During the HORB period, flows measured at SJG were approximately 1,300 cubic feet per second (cfs), with a maximum of 1,700 cfs recorded during Environmental Water Account (EWA) releases (see Figure 6). After the November 10, 2007 removal of the HORB, only 0 to 20% of the Vernalis flow entered the DWSC and net flows approached 0 cfs.

Export pumping from the State Water Project (SWP) and Federal Central Valley Project (CVP) shows that the combined export flow was about 7,000 to 8,000 cfs before and after installation of the HORB (see Figure 8). When the HORB was in place, export flows ranged from 6,000 to 7,000 cfs with a brief dip below 5,000 cfs while the HORB was being removed. These export flows do not seem to explain the lower flow fraction entering the DWSC after the HORB was removed because export flows had decreased.

The drop in the flow fraction entering the DWSC could be caused by the deepening of the bed of Old River during the process of removing the rock barrier. This could allow more water to enter Old River and reduce the flow remaining in the San Joaquin River. Flow diversion fractions since 2004 exhibit a consistent drop in the fraction diverted to the DWSC when comparing values calculated before and after the placement of the HORB (see Figure 9). Thus, the process of removing the HORB may temporarily enhance the flow down Old River, but after approximately 1 month, the bed surface reestablishes itself and the flow fraction approaches levels observed prior to the placement of the HORB. Alternative explanations may be associated with agricultural pumping or downstream barrier operations in the South Delta. For example, the Grant Line and Old River rock barriers were opened 2 to 3 days prior to the breach of the HORB on November 10th. Removal of these barriers would lower the water stage in the South Delta and could enhance flow down Old River. The cause of the drop in the flow split to the DWSC is unknown, it is beyond the scope of this study and a definitive explanation requires further analysis.

2. **What is the effect on DO in the DWSC and San Joaquin River from installing and removing the HORB?**

Longitudinal monitoring from Turner Cut to Mossdale Crossing was performed on approximately a weekly basis before, during, and after the barrier installation during fall 2007. In this 24-mile reach, DO concentrations were typically near saturation from the HOR to river mile (RM) 44 (approximately 4 miles upstream of the DWSC). Except when the HORB was installed, DO levels tended to decline beyond RM 44, reaching a minimum concentration between RM 40 and RM 36 (see Figure 14). Minimum DO concentrations and the DO sag location are summarized in Table ES-1 below. With the HORB and augmenting EWA reservoir releases, net flows of 1,300 cfs were generally sufficient to eliminate the appearance of a DO sag upstream of Turner Cut, the downstream study boundary. Review of DO data recorded by the DWR on October 25 and November 9, 2007 showed that the DWSC DO sag developed farther downstream of the study area.

The installation of the HORB with EWA flow augmentation raised the DO in the DWSC about 1.5 to 2 mg/L above pre-HORB levels. DO concentrations did continue to decline longitudinally 0.6 to 1.6 mg/L from the Port of Stockton (RM 40) to Turner Cut (RM 32.6). Once the HORB was removed, the DO sag redeveloped upstream at RM 38 (near the RRI station). In the absence of high flows, DO concentrations fell from about 9 mg/L to 7.5 mg/L in approximately 5 days at RM 38; however, these concentrations remained higher than levels measured before the HORB installation. As shown in Table ES-1, the lowest DO concentration measured in the DWSC after the HORB removal was approximately equal to or greater than the DO sag prior to the installation. This post-HORB DO decline is consistent with behavior observed in the DWSC during the fall since 2000. Once the HORB is removed, DO in the DWSC will decrease and may approach concentrations observed prior to the installation of the HORB.

Table ES-1. Location of the Minimum Dissolved Oxygen Concentration Measured in the DWSC between Navy Bridge (near Channel Point) and Turner Cut

Monitoring Date	Flow to DWSC SJG at Garwood (cfs)	Head of Old River Status	Station with DO Minimum (RM)	DO Minimum Concentration (mg/L)	Comments
9/19/2007	250	Open	36	6.5	
10/5/2007	440	Open	35	6.4	
10/12/2007	660	Open	34	7.0	
10/25/2007	1,380	HORB in	<32.6	8.3	Sag downstream
11/1/2007	1,915	HORB in	35	8.2	
11/8/2007	1,470	HORB in	<32.6	8.1	Sag downstream
11/15/2007	285	Open	38	7.1	
11/21/2007	150	Open	37	7.4	

3. **Is the HORB beneficial or harmful to the San Joaquin River and the DWSC?**

Assessing changes in water quality from the HORB period is complicated by seasonal changes in temperature, chlorophyll (algae) and flow. During the study period from October 4 to November 21, 2007, the water temperature decreased about 5 degrees Celsius (°C) at each RM station (see Figure 10). Lower temperatures can significantly reduce the rate oxygen is used during the exertion of the biochemical oxygen demand and algal growth and respiration rates. Similarly, chlorophyll *a* and zooplankton concentrations were decreasing prior to the HORB installation on October 17, 2007. However, the effects of the HORB and flow augmentations were still evident.

Conductivity levels decreased from approximately 800 microsiemens/centimeters (µS/cm) to less than 400 µS/cm with the installation of the HORB and augmentation flows from east-side reservoir releases (see Figure 11). With this higher flow (reduced travel time), algae concentrations dramatically decreased from about 30 to10 microsiemens/liters (µg/L) (see Figure 12). When the

HORB was removed on November 10, 2007, chlorophyll *a* concentrations rebounded slightly. The physiological health of the algal community was also assessed with chlorophyll *a* pigment fractions. Decreasing fractions suggest a declining algal community. Before the HORB was installed, chlorophyll pigment fractions markedly decreased from 0.7 to 0.1 in the reach between the HOR and the DWSC. These fractions started to increase with flow before the HORB and continued to increase with the EVA flow augmentation while the HORB was in place. The increased flow associated with the HORB lowers algae concentrations, but these algae exhibit an improved physiological condition above the DWSC. In the DWSC, both algae populations and the chlorophyll *a* pigment fraction decrease significantly, apparently due to grazing by the zooplankton community that had also been displaced by the higher flows from the river to the ship channel.

In terms of the zooplankton community, installation of the HORB translocates the organisms from the SJR into the DWSC; during this movement the biomass (based on concentration) of the organisms greatly decreases (Figure 17 and Figure 30), as does the species diversity (Figure 22). Since the major contributor to the community biomass is the copepod *Pseudodiaptomus forbesi* (pforb), and this species is a major source of food for fish species, the effect of the HORB is to reduce the concentration of this resource. The effects of increased flow from reservoir releases and the advancing season are possibly confounding variables making study of the HORB effect difficult; however, the combined effect of the releases and HORB in increasing net flows into the DWSC seems to be the major factor influencing zooplankton abundance in the DWSC. The decrease in zooplankton biomass and species diversity following the HORB installation is likely a temporary harmful effect on the DWSC ecosystem, as fewer resources are available to higher trophic levels. The potentially confounding effect of seasonal advancement should be considered when interpreting these data. Study of the entire DWSC ecosystem was not in the scope of this investigation, so inferences about higher trophic levels, such as effects on fish habitat quality, cannot be made with confidence. The primary reason for measuring zooplankton and quantifying phytoplankton with chlorophyll measurements was to characterize the primary oxygen demand entering the DWSC and grazing that influences algal decomposition and the exertion rate of its oxygen demand. As discussed earlier, installation of the HORB and EVA flow augmentation was shown to have a dramatic benefit on DO in the DWSC, at the expense of reduced plankton concentrations and diversity.

4. **Can tracking of flow and water quality conditions associated with the installation and removal of the HORB provide information for operating the DWR aeration facility?**

The changes in flow caused by the installation and removal of the barrier causes a rapid change in the flow and BOD concentration entering the DWSC and, therefore, an opportunity to evaluate the response of DWSC water quality.

DO depletion observed in the DWSC appears to be correlated with the flow and the ultimate BOD (BODult) concentrations entering the DWSC. This suggests that a simple DO model may be capable of predicting DO deficits in the DWSC.

Chapter 1
Study Overview

Longitudinal water quality monitoring was performed on the San Joaquin River from Mossdale Crossing to Turner Cut to assess the effects of installing and removing the Head of Old River Barrier (HORB). Figure 1 presents the San Joaquin River Mile (RM) station locations for the water quality monitoring and biological sampling performed for this study. Also shown on the station map are the locations of the continuous monitoring stations at Rough and Ready Island (RRI), the San Joaquin River Garwood Bridge flow station (SJG), Brandt Bridge water quality station (BDT), and the HORB Mossdale Crossing (RM 56.7) and Turner Cut (RM 32.6) represent the upstream and downstream boundaries of the study, respectively.

The installation of the HORB is performed and operated by the California Department of Water Resources (DWR). In conjunction with additional Environmental Water Account (EWA) reservoir releases, more flow is maintained in the San Joaquin River below the HOR to increase dissolved oxygen (DO) concentration for fall Chinook salmon. Historically, these management practices have been successful in temporally elevating DO levels in the Stockton Deep Water Ship Channel (DWSC).

The following study was designed to assess the effects of the HORB on San Joaquin River (SJR) flows, characteristics of flows as they enter the DWSC, loads of oxygen-demanding substances delivered to the channel, and the response of the San Joaquin River and DWSC after the removal of the HORB. In addition, this study may also serve to improve operational management of the aeration system by improving understanding of the response of DO in the DWSC to upstream changes in water flow and quality.

Study Elements

1. Develop the relationship between flow and travel time from the HORB and the DWSC using dye studies.
2. Assess water quality impacts with longitudinal monitoring conducted before, during, and after the installation of the HORB. Measurement of DO, oxygen-demanding substances (e.g., ammonia and algae and biochemical oxygen demands [BODs] tests) and zooplankton (algae grazers) was emphasized.
3. Analyze water quality data for important correlations and calculate loads of oxygen-demanding substances.

Methods and Materials

Tracer Releases to Verify Net Flow

Dye releases were performed periodically to determine the river travel time from the HORB to the DWSC. When zooplankton collection was performed, both day and night runs were scheduled near low and high slack time periods. A rhodamine WT tracer (Keystone Pacific Division, Santa Fe Springs, CA) was introduced to the San Joaquin River below the HORB on 4 days during ebb flows. The dates and times of the dye releases are presented in Table 1. As many as three self-logging fluorescent sensors (Hydrolab DS5X, Hach Inc., Boulder CO, and SCUFA II, Turner Instruments, Sunnyvale, CA) were positioned at fixed locations downstream to record the passing of the dye plume. Dye travel times were estimated by noting the time required for the peak concentration to pass the sensor location. At low net flows, tidal reversals are evident by the passing of the dye plume more than once. The farthest downstream sensor was located at the Outfall Pier (RM 41) located only 1 mile above the DWSC. The travel time to the DWSC was determined from the time of release to the last time the dye completely passed the Outfall Pier. The four dye releases were conducted on dates in which the net flow to the DWSC was estimated to be approximately 300, 700, 1,400, and 1,900 cubic feet per second (cfs) using tidal flow data reported for SJG by the U.S. Geologic Survey (USGS).

Water Quality Monitoring

Longitudinal water quality monitoring runs were performed between RM 32.6 (Turner Cut) and RM 56.7 (Mossdale) from October 4 to November 21, 2007, as shown in Table 1. The September 19 and 20, 2007, monitoring was performed for another study, but these data are valuable in interpreting the pre-HORB installation results (Litton et al. 2008). The profiles started at Turner Cut (RM 32.6) and ended at the Mossdale Crossing Boat Ramp (RM 56.7). Each longitudinal run started at the downstream end of the study at RM 32.6 and tracked the upstream-moving slack tide condition to Mossdale RM 56.7, except for the monitoring run performed on November 1, 2007, in which the direction of sample collection was disrupted by dense fog the previous night. Water samples were also collected at approximately every other site and analyzed for chlorophyll *a*, pheophytin *a*, ammonia, BOD, phytoplankton, and zooplankton.

Sampling was performed by grab methods and analysis was conducted in accordance with standard methods (AHPA 2005). Chlorophyll *a* and pheophytin *a* were extracted using an acetone/water solution and ultraviolet (UV) absorption in accordance with SM 10200H. Biochemical oxygen tests were conducted for 20 days with measurements performed approximately every 5 days (SM 5210 C) to facilitate the determination of decay rate constants. Total ammonia was measured with an ion-specific electrode following SM 4500-NH_3 D.

A continuous recording water profiler (SBE25, Sea-Bird Instruments, Inc. Bellevue, WA) and water quality sondes and (YSI 6600, YSI, Inc., Yellow Springs, OH; Hydrolab 5SDX, Hach Inc., Boulder, CO) were deployed at the longitudinal monitoring sampling stations to measure *in situ* water temperature, conductivity at 25°C (SC), pH, DO, chlorophyll *a* fluorescence, and turbidity. At each station visited, depth profiles were recorded with the SBE25 equipped with a chlorophyll fluorometer and turbidity sensor (SCUFA III, Turner Instruments, Sunnyvale, CA) and a photosynthetically available reactive (PAR) light sensor (Biospherical Instruments, Inc. San Diego, CA). One or two water quality sondes were also deployed at mid depth to provide calibration checks. Calibration of all sondes was performed via Standard Methods and the manufacturer's instructions. In the case of DO measurements, sensors were also checked in DO-saturated water and water void of oxygen (achieved with sodium sulfite and a trace amount of catalyst cobalt chloride). Toward the end of November 2007, calibration checks were also performed to assess the cold temperature response of the instruments.

Continuous water quality measurements were also performed by deploying multi-parameter sondes (YSI 6600, YSI, Inc., Yellow Springs, OH; Hydrolab 5SDX, Hach Inc., Boulder, CO) at three locations above the DWSC. Sondes were placed at the Outfall Pier (OP) RM 41, Stockton Brick Company (SBC) RM 45, and the Brandt Bridge Station (BDT), RM 47.8. Calibration was performed per Standard Methods (APHA 2005) or manufacturer's specifications and checked at the end of deployment. The data acquisition frequency was set to 15 minutes. In addition, the DWR also maintained five water quality monitoring stations in the DWSC. The DWR DWSC data was not used in the development of this report.

Zooplankton Samples and Measurements

To assess the dynamics of the grazing community during the study period, zooplankton were sampled at most of the sites and times used for the measurement of physical and chemical water quality parameters (Table 1. and Figure 1). Zooplankton sampling occurred over five time periods in 2007:

- September 19–20, 2007 (HORB removed; 24 samples);
- October 4–5, 2007 (HORB removed; 18 samples);
- October 24–25, 2007 (HORB installed; 18 samples);
- October 31–November 1, 2007 (HORB installed with EWA flows; 16 samples); and
- November 15, 2007 (HORB removed; 20 samples).

Zooplankton were collected with a 30-liter Schindler-Patalas Trap fitted with a 63-micrometer(µm) mesh net (Wildlife Supply Company, Buffalo, NY). Samples were taken at mid-depth and mid-channel. All samples were preserved in buffered formalin sucrose (60 grams per liter [g/L]) at 5% final concentration, and volumes adjusted to 500 milliliters (mL). Samples were thoroughly mixed by gentle inversion and a 10 mL subsample was taken from each using a Stempel pipette. Subsamples were added to settling chambers (Standard Utermöhl Chamber, Aquatic Research Instruments, Lemhi ID) and settled for at least 10 hours prior to microscopic examination. Rose Bengal dye was added to all subsamples to facilitate enumeration.

Zooplankton were examined with a Leica DM-IL inverted microscope at a magnification of 100 times. Identification of Rotifera followed Chengalath et al. 1971, Pontin 1978, Pennak 1989, Thorp and Covich 1991, and Jersabek et al. 2003. Identification of Cladocera and Copepoda followed Edmondson 1959, Balcer et al. 1984, Pennak 1989, Orsi and Walter 1991, and Thorp and Covich 1991. During the counts, the entire chamber floor was examined. For biomass estimates, body lengths were taken from a maximum of 20 individuals of each species. Conversion of body lengths into dry-weight biomass followed Doohan 1973, Dumont et al. 1975, Bottrell et al. 1976, and Pace and Orcutt 1981. Ciliates were counted, but species were not identified and biomass estimates were not calculated.

Table 1. Schedule of Longitudinal Monitoring Runs and Tracer Release Events

Date	HORB Status	Net Flow to DWSC (cfs)	Range of Longitudinal Profiles San Joaquin River Miles	Tide Conditions	Zooplankton Collected	Date and Time of Dye Release
9/19/2007 9/20/2007	Open	250	34 (9/19 21:20) to 56.7 (9/20 1:45)	Flood	Yes	9/20/2007 2:05
			39.6 (9/20 7:45) to 56.7 (9/20 10:30)	Ebb		
10/4/2007 10/5/2007	Open	440	34 (10/4 23:50) to 56.7 (10/5 3:40)	Flood	Yes	10/5/2007 4:00
			34 (10/5 7:50) to 56.7 (10/5 12:00)	Ebb		
10/12/2007	Open	660	34 (10/12 13:45) to 56.7 (10/12 17:35)	Ebb	No	
10/17/2007	**HOR CLOSED**					
10/18/2007	HORB in place w/notch	1420	none		No	10/18/2007 23:45
10/24/2007 10/25/2007	HORB in place w/notch	1380	34 (10/24 18:05) to 56.7 (10/24 21:05)	Flood	Yes	
			34 (10/25 8:40) to 56.7 (10/25 11:15)	Ebb		
10/31/2007 11/1/2007	HORB in place w/notch	1915	32.6 (10/31 22:10) to 46 (11/1 23:45) (fog ended run)	Flood	Yes	11/1/2007 7:45
			54 (11/1 7:50) to 32.6 (11/1 11:05)	Ebb		
11/8/2007	HORB in place w/notch	1470	32.6(11/8 9:00) to 56.7 (11/8 12:27)	Ebb	No	
11/10/2007	**HOR OPENED**					
11/15/2007	Open	285	32.6 (11/15 7:15) to 56.7 (11/15 10:15)	Ebb	Yes	
			32.6 (11/15 19:45) to 56.7 (11/15	Flood		

Date	HORB Status	Net Flow to DWSC (cfs)	Range of Longitudinal Profiles San Joaquin River Miles	Tide Conditions	Zooplankton Collected	Date and Time of Dye Release
			22:10)			
11/21/2007	Open	150	32.6(11/21 11:08) to 56.7 (13:34)	Ebb	No	

San Joaquin River RM Locations:
32.6: Navigation Light 24 at Turner Cut
34: Navigation Light 32
39.6: Navigation Light 48 at Channel Point
54: Head of Old River Barrier (HORB)
56.7: Launch ramp at Mossdale Crossing

Chapter 2
Results

An overview of the flows entering the study area for 2007 is presented in Figure 2**.** The Vernalis flow is a reasonable representation of the flow entering the upstream study boundary at Mossdale Crossing. In the absence of the HORB, approximately 50% of the Vernalis flow plus 5% of the export pumping flows associated with the State Water Project (SWP) and the Central Valley Project (CVP) flow into Old River from the SJR. The flow remaining in the SJR enters the DWSC approximately 15 miles downstream of the HOR. The USGS Garwood station provides flow measurements of water entering the DWSC. The estimated DWSC flow is calculated by subtracting the Old River flow (50% Vernalis plus 5% export flow) from the Vernalis flow. Net river flows entering the DWSC during October and November 2007 ranged from a low of 83 cfs to a maximum of 1,930 cfs.

Figure 2 shows that all flows exhibit a sharp pulse in October and November 2007 resulting from upstream EWA reservoir releases for migrating salmon. When the HORB is installed, most of this pulse flow—as measured at Vernalis—remains in the SJR and passes through the DWSC. The estimated flow represents what would have passed through the DWSC in the absence of the HORB. As indicated in Figure 2, installation of the HORB more than doubled the flow directed through the DWSC.

Figure 3 presents an overview of the response of the DO to the increased flow pulse directed through the DWSC in October and November 2007. Prior to October and the fall flow pulse, the DO was below the water quality standard of 5 or 6 mg/L. Increased reservoir releases in combination with the installation of the HORB resulted in the rise of the DWSC flow to almost 2,000 cfs. As seen in Figure 3, DO measured at RRI responded quickly with increased flow, reaching a maximum near saturation concentrations of approximately 10 mg/L. Once the pulse flow subsided, DO levels decreased to conditions observed prior to the HORB operation. After the initial decline in DO from removing the HORB on November 11, 2007, DO continued to increase at RRI due to the seasonal reduction in algae load and perhaps the modest rise in DWSC flow. During this October to December 2007 time period, decaying algae entering the DWSC represented one of the significant BODs influencing DO in the channel. The other important source of BOD comes from the City of Stockton's treated wastewater effluent discharge located approximately 1.5 miles upstream of the DWSC. In 2007 Stockton completed a treatment facility upgrade to nitrify its ammonia prior to river discharge. During the October to November 2007 study period, the nitrification units were operating efficiently and effluent ammonia concentrations were usually below detection levels (0.5 mg/L) and never higher than 1.6 mg/L.

Travel Time Estimates using Dye Studies and Flow Measurements

Four dye releases to the SJR below the HOR were conducted to develop the relationship between net flow to the DWSC and travel time from the HORB to the DWSC. Figure 4 presents an example of the dye profiles captured by stationary sensors downstream of the HOR for the tracer released on September 20, 2007 at 2:05 p.m. During the first ebb tide, the dye traveled over 6 miles downstream, before tidal flow reversal carried the plume back upstream. The rhodamine sensor positioned 6.5 miles downstream of the HORB at the DWR BDT shows at least three passes of the plume during ebb tide. The sonde fixed to the Outfall Pier, 1 mile above the DWSC, clearly shows two ebb flow passes before the fluorescent signal is lost to the DWSC. In this case it took approximately 5 days for most of the dye to pass the Outfall Pier, 1 mile above the DWSC. The average net flow at Garwood for this period was 320 cfs. Three other dye releases at the HOR were also performed in October and November 2007, during times when the SJG average net flows of 700, 1,420, and 1,900 cfs yielded HORB to DWSC travel times of approximately 2.8, 1.3, and 0.85 days, respectively, as shown in Figure 5. These travel times can be used to estimate the net flow knowing the average river cross-sectional geometry:

$$Q = wld / t ,$$

W and *d* are the average river depth and *l* is the 14 miles of path length of the SJR from the HORB to the DWSC. Bathymetric data collected for the City of Stockton in 2006 in this reach yield an approximate average cross-sectional river area of 2,300 square feet from RM 48 to RM 40. As shown in Table 2, the net flows associated with the dye travel times are in reasonable agreement with the net flows estimated from instantaneous SJG flow records. Figure 5 provides a relationship for computing travel time from the HOR to the DWSC knowing net river flow.

Table 2. Comparison of Estimated Net Flows Entering the DWSC

Date and Time of Dye Release	SJG Flow Average over Dye Travel Time to the DWSC (cfs)	Dye Travel Time Flow Estimate (cfs)
9/20/07 2:05	320	340
10/5/07 4:00	700	600
10/18 23:45	1,420	1,300
10/25 7:45	1,900	2,000

The average river cross-sectional area can also be determined by plotting the Garwood flow estimates against t^{-1}. The slope of the regression line yields the volume of the river reach between the HOR and the DWSC. The average cross-sectional area using this approach was calculated to be 2,200 square feet, in close agreement with cross-sectional measurements. This average cross-sectional area yields a mid-tide area of approximately 3,700 acre feet, the travel time from which can also be calculated directly.

The net flows from SJG and Vernalis are presented in Figure 6 for the October–November 2007 study period. Vernalis flows represent the total flow entering the San Joaquin River Delta. At the HOR, the flow splits and in the absence of the HORB, the majority of the water travels down Old River, away from the DWSC, (see Figure 1). The pulse of EWA releases is also apparent in Figure 6 as shown by the increase of Vernalis flows from 1,200 cfs to 2,400 cfs yielding an average daily flow to the DWSC of about 1,400 cfs.

Figure 7 displays the percentage of Vernalis flow that passed through the DWSC in October and November 2007. Prior to the installation of the HORB, approximately 40 to 60% of the flow was directed down the SJR to the DWSC. With the HORB in place, 70 to 90% of the flow was routed through the DWSC. In 2007, the rock barrier was installed with a notched spillway to allow the passage of salmon that could potentially become stranded in the south Delta. During this HORB period, flows measured at SJG were approximately 1,500 cfs, with a maximum of 1,930 cfs recorded during EWA releases (shown earlier in Figure 6). After the November 10, 2007, removal of the

HORB, only 10 to 20% of the Vernalis flow entered the DWSC and net flows approached 0 cfs by December 2007.

Figure 8 presents the SWP and federal CVP export flows from the South Delta. These exports will exert an influence on the flow spilt at the HOR. A general approximation for the flow rate entering Old River from the SJR when the HORB is absent is to add 5% of the combined SWP and CVP flow to 50% of the Vernalis flow. Thus, the export pumping would influence the flow split before and after the HORB period by directing an additional 350 cfs away from the DWSC, since the combined export flow was about 7,000 cfs. However, export flows were actually about 500 cfs lower after the HORB was removed when compared with combined pumping before the HORB placement. Therefore SWP and CVP export flows do not appear to have caused the drop in the flow fraction entering the DWSC after the HORB was removed.

Figure 9 compares the flow fraction to the DWSC for years 2004 to 2007. For these years the flow fraction dropped to 0.1 to 0.2 immediately after the HORB was removed. However, the flow fraction continued to increase through December 2007 after reaching a low of 0.1 in November. This pattern suggests that the drop in flow fraction entering the DWSC could be caused by the deepening of the river bed below the HORB when it is removed each year. With time, the river bed reestablishes itself as inflowing sediment fills the excavation. Alternative explanations might also be associated with downstream barrier operations or agricultural pumping in the South Delta. These alternatives were not investigated and the cause of the drop in the flow fraction to the DWSC remains unknown.

Residence times using for water routed from the HOR through the DWSC were calculated assuming plug-flow hydraulics (see Figure 5) and are presented in Table 3. The effect on net flow is quite dramatic. For a net flow of 1,700 cfs entering the DWSC in October and November 2007, the travel time was estimated to be approximately 0.9 day to reach the DWSC and then another 3.4 days to reach Turner Cut. Net flows of 250 cfs require 29 days to make the journey from the HOR to Turner Cut. At the lowest net flow of 100 cfs, the travel time increases to over 100 days. While these residence times do not reflect transport associated with tidal flow dispersion, they do provide insight into the time scales required for a parcel of water to move through the study reach and the time available for oxygen-demanding substances to exert their demand while in the DWSC. The travel time implications are also important when viewing longitudinal water quality profiles of measurements performed between the HORB and Turner Cut on a single day as the water at Turner Cut may have passed the HOR weeks earlier if net flows are less than 500 cfs. Similarly, oxygen demands of water entering the DWSC will be completely exerted before the water exits at Turner Cut for these low net flows.

Table 3. Estimated Travel (Residence) Times from the HORB to Turner Cut

Date	Flow to DWSC (cfs)	HORB Status	Travel Time HORB (RM 54) to DWSC (RM 40) (days)	Travel Time DWSC (RM 40) to Turner Cut (RM 32.6) (days)	Total Travel Time HORB (RM 54) to Turner Cut (RM 32.6) (days)
9/19/2007	250	Open	6.7	24	31
10/5/2007	440	Open	3.9	14	18
10/12/2007	660	Open	2.6	9	12
10/25/2007	1,380	Installed	1.3	4.3	5.6
11/1/2007	1,915	Installed	0.9	3.1	4.0
11/8/2007	1,470	Installed	1.2	4.1	5.3
11/15/2007	285	Open	6.0	21	27
11/21/2007	150	Open	11	40	51

Water Quality Responses to the HORB Installation

The longitudinal temperature profiles from Turner Cut (RM 32.6) to Mossdale (RM 56.7) are presented in Figure 10 for water quality monitoring performed before, during, and after the HORB installation. Green symbols represent pre-HORB monitoring, red markers identify data collected while the HORB was installed, and blue denotes post-HORB monitoring. This convention is maintained for all the longitudinal parameter figures (i.e., Figure 10 to Figure 15). As shown in Figure 10, the water temperature dropped about 7°C from September 19 to November 21, 2007. The decline in temperature appears to be mostly caused by seasonal cooling. It is not clear whether the lower temperatures observed when the HORB was in place were influenced by cooler reservoir release waters. Perhaps the most significant benefit of the cooler water is the increased DO saturation concentrations. For example, the 21°C water in September 2007 had a saturated concentration of 8.95 mg/L, but increased to 10.31 mg/L in late November 2007 when temperatures fell to 14°C. Thus, the cooler water contributed to raising DO concentration during the fall HORB period.

The conductivity longitudinal profiles provide a signal of how water is displaced in the DWSC at higher net flows. The greatest drop of conductivity across the study reach (RM 56.7 to RM 32.6) was observed in September 2007, before the installation of the HORB. The conductivity at Mossdale exceeded 800 µS/cm, but was only about 330 µS/cm at Turner Cut. The near-zero net flows measured most of the summer and early fall had little influence on the low conductivity Sacramento River water that mixes with the SJR at Turner Cut. As net flows increased to 500 cfs in early October 2007 before the HORB was installed, the conductivity increased to about 600 µS/cm. With the increased flow during the HORB period, the conductivity was nearly constant in the study reach, suggesting that the flow was sufficient to displace most of the Sacramento River water at Turner Cut. In addition, the east-side reservoir released to complement the HORB installation dropped electrical conductivity (EC) at the HORB from about 750 to 450 µS/cm. Also evident in the DWSC profiles was the time required to displace all the DWSC channel water at flows of 1,300 and 1,700 cfs. The November 8 2007 profiles suggest that about 2 weeks of higher flows are required to displace the higher conductivity water. As soon as the HORB was removed, net flows fell to near zero and the pre-HORB conductivity profile reappeared. The upstream influence became more pronounced when the net flow fell to 150 cfs on November 21, 2007. The EC data are similar in pattern to the zooplankton biomass data, showing translocation of river water through the DWSC during HORB installation. Also, when *Eurytemora* appeared, likely from Sacramento River water, it was after the HORB had been removed.

The chlorophyll *a* longitudinal profiles are shown in Figure 12. As with the water temperature plots, the continuing seasonal decline in algae had a strong effect on the chlorophyll concentrations from late September through November 2007. Pre-HORB monitoring in October 2007 showed significant concentrations of chlorophyll *a* below the HOR, reaching a maximum near the Stockton Brick Company (SBC), about 5 miles above the DWSC. Downstream of the SBC, chlorophyll *a* declined sharply from about 40 µg/L to less than 10 µg/L below the RRI station in the DWSC. This sharp decline appeared to be well correlated with zooplankton populations (shown and discussed later in this document). The flow augmentation associated with the HORB installation had a dramatic impact on chlorophyll above the DWSC. The early reservoir releases appeared to dilute the chlorophyll *a* in the SJR above the HORB from about 30 to 20 µg/L. Higher EWA flows drive the chlorophyll *a* concentration to10 µg/L. Once the reservoir releases ceased, the chlorophyll *a* levels seemed to recover slightly above the DWSC. In the DWSC, regardless of flow, chlorophyll *a* crashed dramatically, a phenomenon attributable to the greater light shading over a deeper water profile. However, the zooplankton population did not recover with the removal of the HORB.

The fraction of chlorophyll *a* to the sum of chlorophyll *a* and pheophytin *a* provided a measure of the physiological health of the algae populations (APHA 2005). Healthy communities have high chlorophyll *a* pigment fractions. Figure 13 presents the pigment fraction before, during, and after the installation of the HORB. Near-zero flow conditions are quite detrimental to algal populations as shown with the September 20, 2007 monitoring data. The pigment fraction drops from 0.7 µg/L at the HOR to almost 0.1 µg/L at the DWSC. With the increased river depth downstream of the HOR and generally high turbidity of the water, the fraction of the water column in which photosynthesis can occur decreases significantly. When the lower algal productivity, associated with increased river depth, is combined with increased zooplankton grazing the algal community health is affected. As flows increased to about 500 cfs by mid-October, the decline in the pigment fraction was pushed downstream toward the DWSC and was not as severe, probably largely due to the reduced residence time influencing algal growth and decay. With the installation of the HORB and augmentation flows, the pigment fraction remained relatively constant at 0.7 from Mossdale to the DWSC. This was likely due to the short residence (travel) time of approximately 1 day for the algae to travel from the HORB to the DWSC (see Figure 5). This behavior may also have been caused by the downstream displacement of the zooplankton to RM 38 in the DWSC. The pigment fraction began to exhibit its characteristic decline with the HORB, but not until the algae reached the DWSC. With the removal of the HORB in late November 2007, the start of the algae community decline shifted upstream again and exhibited a sag in the DWSC at about RM 36. Downstream of RM 36 the pigment fraction started to recover, perhaps due to the influence of Sacramento River water at Turner Cut.

Oxygen Demands and Loads

The DO concentrations from Turner Cut (RM 32.6) to Mossdale (RM 56.7) are shown in Figure 14. Note that the DO concentrations exhibit a very similar behavior to the chlorophyll *a* pigment fraction shown earlier in Figure 13. The greatest decline in DO was observed on September 20,

2007. Concentrations decreased from near 11.0 mg/L at HOR to 6.5 mg/L in the DWSC. Net flows above 500 cfs were capable of maintaining relatively constant DO concentrations in the 14-mile reach from the HOR to the DWSC. However, DO began to decline upon entry to the DWSC, as did the chlorophyll *a* pigment fraction.

In the absence of the HORB, a DO minimum is observed in the DWSC upstream of Turner Cut. Table 4 presents the location of the minimum, the respective DO concentration at the sag, and the change in the DO from the HORB to the DWSC sag. Prior to the HORB, the change in DO concentration from the HOR to the DWSC varied from 2.0 to 4.3 mg/L. With the HORB installed and augmentation flow, the change in DO decreased to a minimum of 0.6 mg/L for the highest net flow of 1,900 cfs. Removal of the HORB and the associated reservoir releases yielded an increase in DO concentration to 2.4 mg/L on November 21, 2007, 11 days after the HOR was removed.

Table 4. Location of DO Sag Minimum Concentration Measured in the DWSC between Navy Bridge (near Channel Point) and Turner Cut

Date	Flow to DWSC (cfs)	HOR Status	Station with DO Minimum (RM)	DO Minimum Concentration (mg/L)	DO Change HORB to Sag (mg/L)	Comments
9/19/2007	250	Open	36	6.5	4.3	
10/5/2007	450	Open	35	6.4	3.9	
10/12/2007	500	Open	34	7.0	2.0	
10/25/2007	1,250	HORB in	<32.6	8.3	1.6	No DO sag
11/1/2007	1,750	HORB in	<32.6	8.2	0.6	No DO sag
11/8/2007	1,300	HORB in	<32.6	8.1	1.7	No DO sag
11/15/2007	160	Open	38	7.1	1.8	
11/21/2007	60	Open	37	7.4	2.4	

The HORB and augmentation flows also pushed the DO minimum concentration in the DWSC to Turner Cut (RM 32.6) or beyond. As presented in Table 4, the low net flows observed without the HORB installed yielded a DO sag within the DWSC above Turner Cut. Inspection of the DO sag locations with the net flow indicates that the sag is closest to the aeration facility at RRI at values less than approximately 200 cfs. Net flows approaching 500 cfs push the sag point downstream about 3 to 4 miles of the aeration facility.

BOD_{ult} concentrations were measured for selected water samples collected during the longitudinal monitoring. The BOD_{ult} was determined from BOD test conducted over 20 days. These data are available in the appendix along with the results of the first-order line fits used to determine the kinetic decay constant, k, and the BOD_{ult}.

$$BOD_t = BOD_{ult}(1 - e^{-kt})$$

In general the first-order decay expression (shown above) yielded excellent fits to the observed data. For a few data sets, the fit was not satisfactory and in these cases the BOD_{ult} was estimated from the BOD_{20} experimental results. A strong linear correlation using over 100 data sets established that the BOD_{ult} was equal to 1.1 times the BOD_{20}.

The BOD_{ult} concentrations shown in Figure 15 also exhibit a similar pattern to the DO concentration shown earlier in Figure 14. Prior to the installation of the HORB, the BOD_{ult} levels remained relatively constant above the DWSC, but decreased rapidly with distance downstream of Navy Bridge (Channel Point). With the installation of the HORB, the BOD_{ult} of the water routed to the DWSC at the HORB was about 2 mg/L lower than during pre-HORB conditions. The decline of BOD_{ult} in the DWSC was also much less than observations before the HORB, a phenomenon probably associated with the reduced residence time associated with larger net flows passing through the DWSC as shown earlier in Table 3. Once the HORB was removed, the BOD_{ult} in the study reach changed very little. This could be due to the relatively low chlorophyll *a* concentrations characteristic of late fall conditions of the San Joaquin River.

The sum of chlorophyll *a* and pheophytin *a* is plotted against the BOD_{ult} concentrations for data collected in October and November 2007 in Figure 16. This comparison suggests that most of the oxygen demands during this study were not associated with algae. At most, the algae concentration contributed about 3 mg/L of oxygen demand. At near-zero algae concentrations, the ultimate BOD approaches 3.7 mg/L.

The loads of known oxygen demands entering the study reach are tabulated in Table 5. Daily loads are calculated from the flow and concentration data. The BOD_{ult} loading for the City of Stockton was calculated from monitoring data reported to the Regional Water Quality Control Board, a waste discharge requirement. The City of Stockton typically discharges approximately 32 million gallons per day (MGD) (50 cfs) of wastewater to the San Joaquin River at RM 41.5. The load was calculated from carbonaceous BOD (cBOD) tests and total ammonia concentrations in their effluent. For the October 5 to November 8, 2007 dates the cBOD test results were less than a 2.0 mg/L detection limit, and ammonia was less than a 0.5 mg NH3-N /L detection level. For these calculations, the detection limits were used and, therefore these loads were overestimates. They are shown largely for comparison purposes. Comparing the City of Stockton's DO demands with the loads coming from the San Joaquin River indicates that at net flows greater than about 500 cfs, the wastewater effluent contribution was less than 10% of the load below the HOR. Stockton's low contribution to the BOD entering the DWSC is largely associated with its facility improvements to nitrify ammonia prior to discharge. The fraction of BOD exerted in the DWSC was estimated from the travel time (see Table 3) through the DWSC to Turner Cut, a distance of 7.4 miles and calculated by where k was set to 0.11 1/d, a value common to the BOD tests performed for this study.

$$\frac{BOD}{BOD_{ult}} = 1 - e^{-kt},$$

These calculations suggest that for flows greater than 500 cfs, approximately 12,000 to 13,000 pounds per day (lb/d) of DO is consumed during the exertion of the incoming oxygen loads. However, the DO sag during this time was relatively small, and DO concentrations consistently remained above 6.5 mg/L. Net changes in DO concentration entering and leaving the DWSC study reach suggest that the oxygen demand exerted is approximately 6,000 lb/d. However, during this period with rapidly changing flows, direct calculation of the change in DO concentrations assumed that steady-state concentrations of DO were achieved for each day of estimation. Inspection of the travel times for the net flows suggests this was not the case. Atmospheric and engineered reaeration may also offset these DO demands, but estimates are not provided here. Due to the highly variable nature of the flow and BOD loads during the study period, a water quality model is probably needed to use these data as a predictive tool to assist with future operations of the aeration facility.

Table 5. DO Demand Loads Entering the DWSC and Estimate of DO Exerted Based on Long-term Laboratory BOD Experiments

Date	Flow to DWSC (cfs)	HOR Status	BOD_{ult} HORB (lb/d)	BOD_{ult} City of Stockton* (lb/d)	Travel Time DWSC, RM0 to Turner Cut RM32.6 (d)	Fraction of BOD Exerted in DWSC	BOD Exerted in DWSC (lb/d)
10/5/2007	450	Open	15765	1371	14	0.77	13000
10/12/2007	500	Open	14822	1371	9	0.63	12000
10/25/2007	1,250	HORB in	30318	1371	4.3	0.37	13000
11/1/2007	1,750	HORB in	40559	1371	3.1	0.29	13000
11/8/2007	1,300	HORB in	28728	1371	4.1	0.36	12000
11/15/2007	160	Open	4312	2710	21	0.90	6900
11/21/2007	60	Open	1746	1493	40	0.99	3200

* Based on discharge flow of 32 MGD

Biological Analysis of Zooplankton

Dominant Zooplankton Species

During the entire study period, 32 species of rotifers, four species of copepods, and six species of cladocerans were observed (Table 6). Nauplii (larval copepods, of mixed species, the species not separable) were present throughout all samples for all periods except for September 19-20, 2007, at RM 56 (high-high tide, night), and October 24-25, 2007, at RM 56.8 (low-low tide, day). *Synchaeta longipes* were present in all samples for the October 24-25, 2007 and October 31-November 1, 2007 periods; in no other case was a species present in all sites during a period. Species representing the greatest biomass were as follows (species under 10% of the total biomass for a period not listed): 1

- September 9-20, 2007 - *Brachionus calyciflorus* (Rotifera; 18% of total biomass during period) and *Pseudodiaptomus forbesi* (pforb, a copepod) (15.4%);
- October 4-5, 2007 -pforb (11.7%);
- October 24-25, 2007no single species over 10%;
- October 31–November 1, 2007 pforb (25%); and
- November 15, 2007 - pforb (39.2%).

Pforb is generally the dominant species of zooplankton in terms of proportion of total biomass, except during the October 24-25, 2007 period (after HORB installation), where no single species dominates. This is significant in that pforb is likely a major source of food for fish species. In terms of actual biomass, pforb in the DWSC takes a large drop after the flows increase (HORB is installed) (Figure 17), with chlorophyll *a* showing an inverse relationship, suggestive of a predator-prey interaction. In the upper reach, at and above RM 40, the drop in pforb is present but not as large. In the entire study reach the pforb population recovers somewhat during the last two sample periods (HORB installed w/EWA flows and HORB removed). Nauplii (larval copepods), which are the most ubiquitous organisms in the study and which are the likely source of the adult pforb observed, undergo a five-fold decrease in biomass in the upper reach after the HORB is in place (Figure 18); however, such a drop does not occur in the DWSC but rather a slight increase when the HORB is in place, suggesting advection of nauplii during the higher flows. Nauplii biomass drops during the last two periods, with no recovery as in pforb. It can be seen that pforb biomass was in decline before the HORB installation, and the population recovers somewhat during the EWA flows and after the HORB is removed. The lateness of the season could be a contributing factor in the decline of pforb, but this does not account for the entire pattern as the pforb population increases into November. Therefore, the relationship between pforb abundance and flow is not very clear, but the lowest numbers are found just after HORB installation. Of special note is the species *Eurytemora affinis*, a copepod, which was seen only during the November 15, 2007 period at site RM 34 (low-low tide, day). In previous studies of the San Joaquin River (RM 40 to RM 72) extending back to 2005, this species had never been observed. This species is characteristic of the deeper, more saline regions of the Delta such as Suisun Bay. In this study it appears in the DWSC only after the period of strong flows induced by the HORB and EWA flows.

Species Diversity

Overall species diversity (number of species) varied greatly during the course of the study, with higher diversity seen in the earlier sampling periods and reduced diversity as the season progressed (Figures 19 through 22). The highest diversity, 23 species, was seen in the September 19-20, 2007 period, at RM 44 (high-high tide, night). The lowest diversity, one species, is seen in the November 15, 2007 period at RM 50 (low-low tide, day) and RM 32 (both at high-high and low-low tides, night and day). For RM 50, only the rotifer *Synchaeta longipes* was present; for RM 32, only pforb was present. Longitudinal profiles indicate that species diversity is highest between RM 44 and RM 40 during the first two sample periods, and generally low in the DWSC and upstream of RM 50. After the HORB installation, the peaks of species diversity are pushed out into the DWSC between RM 38 and RM 36. Also, the species diversity upstream of the HORB, at RM 56.8, is lower after HORB installation. This could indicate a seasonal effect or the effect of reservoir releases upstream. Diversity is most suppressed during the EWA flows, and stay low during the last sample period, although the diversity peak does move back into the mouth of the San Joaquin River at RM 40 as flows fall to zero. As can be seen in Figure 22, the overall downward linear trend occurs for species diversity, with the HORB installation coinciding with an extra amount of decrease in species diversity. Again, a late season could be a contributing factor to overall species decline.

Patterns of Zooplankton Biomass

Estimates of zooplankton biomass for each sample period and site were calculated (Tables 7 though 11 and Figures 23 through 26). Overall zooplankton biomass is generally well correlated with species diversity patterns for each sample period, that is, areas of higher species diversity have higher biomass. Nauplii account for the highest biomass during all sampling periods except 15 Nov, where pforb dominated. This shift from larval to adult forms could be a developmental phenomenon. Zooplankton biomass is always higher during nighttime high-high tide conditions and lower during daytime low-low tide conditions. Prior to the installation of the HORB, zooplankton levels were high, peaking during night high-high tide conditions at 181.6 ug/L at RM 48 during the

September 19-20, 2007 period, and at 175.2 ug/L at RM 46 during the October 4-5, 2007 period. These large zooplankton populations travel with the tidal flow, being pushed downstream during the low-low tide period and upstream during the high-high tide period. During the September 19-20, 2007 period, the population peak moved between RM 48 and 44, and during October 4-5, 2007, it moved from RM 46 to 42, which is consistent with the tidal flow excursion. During these two sample periods, zooplankton levels are low upstream at Mossdale and again low downstream of RM 40. Installation of the HORB and reservoir releases on October 17, 2007, greatly increased net flows into the DWSC (approximately 500 cfs to 1,500 cfs; Figure 6) and decreased residence time from approximately 2.5 days to just over one day (Figure 5). Samples taken soon after the HORB installation (October 24–25, 2007) show a strong decrease in zooplankton levels, falling 66% from the previous sampling period of October 4–5, 2007 (highest peak decreases from 175.2 ug/L to 60 ug/L). Also, the position of the highest peak moved downstream from RM 46 to RM 38, that is, from the San Joaquin River into the DWSC. The peak at RM 38 remains in place for the remaining zooplankton sample periods. This pattern is similar to the aforementioned pattern in diversity.

Relationship of Zooplankton to Photosynthetic Pigment

Comparison of photosynthetic pigment (chlorophyll a and pheophytin a) profiles and zooplankton biomass (Figures 23 through 25) indicate that photosynthetic pigments are high during the first two sampling periods (prior to HORB installation), and that the pigment peaks are 2 to 8 miles upstream of the zooplankton peaks. After HORB installation and subsequently, pigment levels are suppressed however sites with higher pigment are still upstream of the major zooplankton populations. In the first two sample periods (Figure 23), the general drop off of pigment (between RM 52 and RM 46) is followed by a similar drop in zooplankton populations further downstream. The dynamics of this pattern are less obvious in the latter three sample periods. The pattern suggested by Figure 23 is generally consistent with the dynamics of a predator-prey relationship.

The chlorophyll *a* to total pigment ratio is a general measure of the physiological health of the phytoplankton community, where high ratios suggest healthy algae and low ratios suggests algae that are degrading. Pigment ratio in relation to total zooplankton biomass is shown in Figures 27 through 29. It can be seen that in the upper reach, above the major zooplankton peaks, a negative correlation exists between zooplankton biomass and pigment ratio, with the ratio falling as zooplankton increase, suggesting grazing. Further downstream, after the main zooplankton peak, the relationship between zooplankton and the pigment ratio is varied, with no clear pattern present. It should be noted that during the night flood tides, pigment ratio generally increases at the most downstream sample locations, suggesting a recovery of the algal community, however a more likely explanation would be cross-Delta flow contributing water from the Sacramento River. This could also explain the presence of *Eurytemora affinis* in this general area. This species, along with a fresher algal community, could have moved up into the DWSC during flood tide conditions.

Pre-HORB, HORB Installed, and post-HORB Patterns

When zooplankton biomass data and total photosynthetic pigment data are classified into pre-HORB, HORB installed, and post-HORB periods, and the data are standardized to percent of maximum biomass or pigment per sample period, plots of means for these parameters per sample location (data for zooplankton shown in Figure 30) indicate that for zooplankton, the community is translocated from RM 46 to RM 38 when the HORB is installed, and after HORB removal no clear peak of biomass is obvious (actual biomass values after HORB removal are very low). Therefore, the

HORB results in an increase in food resources for fish in the DWSC, but reduces it in the river. Also, in the DWSC the biomass of pforb, the most important zooplankton species in the system (Figure 17), falls eleven-fold. Taken together, it can be seen that the zooplankton community moves into the DWSC and diminishes. There is an inverse relationship between zooplankton biomass and flow entering the DWSC (Figure 26); however, an increase in biomass does not occur following the reduced flows existing after removal of the HORB. As for pigment (data not shown), generally it begins a steady decrease starting at about RM 52 and continues into the DWSC. There is no significant difference in pigment profile between pre-HORB, HORB in, and post-HORB periods. The decline in pigment begins as the zooplankton population increases, again suggesting a predator-prey relationship. Location of zooplankton biomass peaks in relation to tidal and net flows (Figure 31) shows that increased net flow into the DWSC pushes biomass peaks further downstream. Peak biomass in the November 15, 2007 period remains in the same general location as the in the previous two sampling periods (RM 38 and lower) despite greatly reduced flow (the HOR was opened 5 days prior to this sampling event). It is assumed that insufficient time and/or food resources prevented the population from migrating back upstream into the river.

Biomass Patterns by Taxonomic Grouping

When overall biomass is broken down into the broad taxonomic categories of Rotifera, Copepoda, and Cladocera (Figure 32), it is seen that the major contributor to biomass during each sample period is the Copepod group, generally contributing over 80% of the biomass (range 78% to 87%). There is no clear trend over the five sample periods in copepod biomass. For rotifers, however, which generally contribute from 3% to 21% of the biomass, a clear trend exists where rotifer contribution is diminished with the advancing season. The transition from October 4-5, 2007 (HORB removed) to October 24-25, 2007 (HORB installed) has little effect on the group representation, however during the subsequent two periods (October 31–November 1, 2007 and November 15, 2007) a pattern of reduced rotifer and increased cladoceran contribution occurs. Changes in water quality or flows could account for this change, or seasonal effects could be major factor influencing this pattern. Comparison of taxonomic group by river position (Figures 33 through 37) indicates that rotifers and copepods generally coexist, and that rotifers usually become diminished in the DWSC whereas cladocerans increase in the DWSC, although during the October 31–November 1, 2007 period (EWA flows) cladocerans increased in the upper reach (RM 38 to RM 42). For the transition period from October 4-5, 2007 (HORB out) to October 24-25, 2007 (HORB installed), the major effect was to push the community further out into the DWSC, but the composition of the community changed little in broad taxonomic groupings. An added observation was that during the October 31–November 1, 2007 sample period, a bloom of the colonial diatom *Asterionella* occurred from RM 46 to RM 40 during high-high tide at night, and from RM 54 to RM 36 during low-low tide at day. It is likely that this diatom was present above RM 46; however, fog prevented sampling in that reach. In previous studies of the San Joaquin River, such a bloom has not been observed. It occurred about 2 weeks after the installation of the HORB. The cause and effect of this bloom is not understood; however, this is a common lake-dwelling species (including dam lakes) and upstream reservoir releases could have provided a seed source. The bloom had disappeared by the November 15, 2007 sampling.

To summarize the changes in the zooplankton community before and after the HORB installation, the pattern was seen to be one of decline in species diversity and biomass which largely coincided with the HORB installation. The most important members of the zooplankton community were copepods and nauplii, and there numbers are greatly diminished during the study. Whether these changes were seasonal effects is not clear, but a downward trend started even before the HORB installation. The high flows resulting from the HORB installation and EWA program clearly had the effect of moving the community downstream, into the DWSC, and lowering the biomass of pforb, the presumed major food for fish. Following the removal of the HORB, the community did not regain its biomass losses, but there was evidence that it moved back upstream to some degree as net flows dropped to zero.

Table 6. Systematic List of Zooplankton Taxa Collected during the Study Period

ROTIFERA

Asplanchnidae
Asplanchna priodonta Gosse, 1850
Asplanchnopus multiceps (Schrank, 1793)

Brachionidae
Anuraeopsis fissa (Gosse, 1851)
Brachionus angularis Gosse, 1851
B. budapestinensis Daday, 1885
B. calyciflorus Pallas, 1776
B. caudatus Barrois & Daday, 1894
B. havanaensis Rousselet, 1911
B. quadridentatus Hermann, 1783
B. rubens Ehrenberg, 1838
B. urceolaris Müller, 1773
Keratella cochlearis (Gosse, 1851)
K. tropica (Apstein, 1907)

Collothecidae
Collotheca pelagica (Rousselet, 1893)

Conochilidae
Conochilus dossuarius (Hudson, 1875)

Epiphanidae
Epiphanes senta (Müller, 1773)

Euchlanidae
Euchlanis dilatata Ehrenberg, 1832

Filiniidae
Filinia longiseta (Ehrenberg, 1834)

Gastropodidae
Ascomorpha saltans Bartsch, 1870

Hexarthridae
Hexarthra mira (Hudson, 1871)

Lecanidae

Synchaetidae
Ploesoma hudsoni (Imhof, 1891)
Polyarthra remata (Skorikov, 1896)
Synchaeta longipes Gosse, 1887

Testudinellidae
Testudinella patina (Hermann, 1783)

Trichocercidae
Trichocerca similis (Wierzejski, 1893)
T. rousseleti (Voigt, 1901)

Trichotriidae
Trichotria longipedis Myers, 1942

CLADOCERA

Bosminidae
Bosmina longirostris (O. F. Müller, 1776)

Chydoridae
Monospilus dispar G. O. Sars, 1861

Daphniidae
Ceriodaphnia lacustris Birge, 1893
Daphnia parvula Fordyce, 1901

Macrothricidae
Macrothrix laticornis (Jurine, 1820)

Sididae
Diaphanosoma brachyurum (Liévin, 1848)

COPEPODA

Calanoida: Temoridae
Eurytemora affinis (Poppe, 1880)

Calanoida: Pseudodiaptomidae
Pseudodiaptomus forbesi (Poppe & Richard, 1890)

Unidentified *Lecane*
L. bulla (Gosse, 1851)
L. dysorata Myers, 1942

Lepadellidae
Colurella adriatica Ehrenberg, 1831

Mytilinidae
Lophocharis salpina (Ehrenberg, 1834)

Cyclopoida: Cyclopidae
Microcyclops rubellus (Lilljeborg, 1901)

Harpacticoida
Unidentified Harpacticoid species

Table 7. Zooplankton Density (Organisms/L) and Biomass (Dry Weight ug/L) Data—September 19-20, 2007

	RM	Date	Time	Total Zoo Density	Total Zoo Biomass	Rotifer Density	Rotifer Biomass	Copepod Density	Copepod Mass	Cladoceran Density	Cladoceran Biomass	Ciliate Density
High-High Tide, Night	34	9/19/2007	21:20	48.3	54.96	3.33	1.62	40.00	48.34	5.00	5.00	0.0
	36	9/19/2007	21:45	55.0	24.67	0.00	0.00	55.00	24.67	0.00	0.00	0.0
	38	9/19/2007	22:15	111.7	62.07	33.33	0.58	73.33	59.59	5.00	1.91	0.0
	40	9/19/2007	22:50	256.7	40.2	173.33	3.86	81.67	34.56	1.67	1.76	8.3
	42	9/19/2007	23:15	271.7	46.0	173.33	5.60	95.00	39.26	3.33	1.16	1.7
	44	9/19/2007	23:30	333.3	136.7	230.00	66.58	96.67	68.56	6.67	1.59	6.7
	46	9/19/2007	23:45	836.7	127.1	671.67	28.30	165.00	98.79	0.00	0.00	1.7
	48	9/20/2007	0:15	1420.0	181.6	1161.67	57.81	258.33	123.81	0.00	0.00	6.7
	50	9/20/2007	0:30	906.7	155.8	625.00	28.78	281.67	127.03	0.00	0.00	0.0
	52	9/20/2007	0:55	441.7	110.8	201.67	8.14	240.00	102.65	0.00	0.00	5.0
	54	9/20/2007	1:15	146.7	38.4	61.67	2.66	81.67	33.15	3.33	2.59	3.3
	56	9/20/2007	1:30	33.3	1.7	33.33	1.70	0.00	0.00	0.00	0.00	18.3
	56.8	9/20/2007	1:45	63.3	5.2	56.67	2.24	5.00	2.00	1.67	1.00	6.7
Low-Low Tide, Day	40	9/20/2007	7:45	371.7	61.8	251.67	8.90	120.00	52.88	0.00	0.00	3.3
	42	9/20/2007	8:15	855.0	80.9	741.67	30.75	113.33	50.17	0.00	0.00	3.3
	44	9/20/2007	8:30	1261.7	166.0	936.67	36.90	323.33	128.70	1.67	0.43	3.3
	46	9/20/2007	8:50	513.3	99.8	305.00	10.62	208.33	89.13	0.00	0.00	5.0
	48	9/20/2007	9:05	258.3	53.6	140.00	4.89	118.33	48.71	0.00	0.00	3.3
	50	9/20/2007	9:25	75.0	12.0	46.67	1.32	28.33	10.67	0.00	0.00	1.7
	52	9/20/2007	9:45	65.0	8.7	46.67	1.82	18.33	6.90	0.00	0.00	0.0
	54	9/20/2007	10:00	35.0	3.2	28.33	0.96	6.67	2.23	0.00	0.00	3.3
	56	9/20/2007	10:20	20.0	1.9	16.67	0.61	3.33	1.33	0.00	0.00	6.7
	56.8	9/20/2007	10:30	28.3	2.4	23.33	0.39	5.00	2.00	0.00	0.00	3.3

Table 8. Zooplankton Density (Organisms/L) and Biomass (Dry Weight ug/L) Data—October 4-5, 2007

	RM	Date	Time	Total Zoo Density	Total Zoo Biomass	Rotifer Density	Rotifer Biomass	Copepod Density	Copepod Mass	Cladoceran Density	Cladoceran Biomass	Ciliate Density
High-High Tide, Night	34	10/4/2007	23:50	86.3	38.97	22.33	0.37	61.67	37.39	2.33	1.21	0.3
	36	10/5/2007	0:20	83.3	40.24	15.00	0.25	65.00	38.31	3.33	1.68	0.0
	38	10/5/2007	0:40	216.7	38.85	146.67	5.76	66.67	31.19	3.33	1.90	5.0
	40	10/5/2007	1:10	348.3	57.2	251.67	12.09	95.00	43.40	1.67	1.76	10.0
	42	10/5/2007	1:25	578.3	118.9	360.00	25.37	211.67	91.16	6.67	2.38	25.0
	46	10/5/2007	1:55	555.0	175.2	140.00	4.69	415.00	170.53	0.00	0.00	11.7
	50	10/5/2007	2:35	185.0	68.4	30.00	1.22	155.00	67.19	0.00	0.00	16.7
	54	10/5/2007	3:15	61.7	15.3	25.00	0.41	36.67	14.85	0.00	0.00	11.7
	56.8	10/5/2007	3:40	56.7	5.1	51.67	1.92	5.00	3.18	0.00	0.00	8.3
Low-Low Tide, Day	34	10/5/2007	7:50	58.3	22.6	5.00	0.06	46.67	18.79	6.67	3.73	1.7
	36	10/5/2007	8:15	253.3	41.7	158.33	2.24	86.67	34.86	8.33	4.56	5.0
	38	10/5/2007	8:40	390.0	58.5	276.67	13.39	111.67	43.02	1.67	2.05	20.0
	40	10/5/2007	9:15	165.0	32.5	90.00	3.39	75.00	29.14	0.00	0.00	5.0
	42	10/5/2007	9:45	456.7	142.0	175.00	30.17	281.67	111.80	0.00	0.00	28.3
	46	10/5/2007	10:05	228.3	74.2	48.33	1.33	178.33	71.85	1.67	1.00	13.3
	50	10/5/2007	10:45	103.3	24.2	48.33	2.36	55.00	21.81	0.00	0.00	13.3
	54	10/5/2007	11:30	70.0	6.2	58.33	1.51	11.67	4.67	0.00	0.00	8.3
	56.8	10/5/2007	12:00	53.3	3.3	48.33	1.48	5.00	1.83	0.00	0.00	5.0

Table 9. Zooplankton Density (Organisms/L) and Biomass (Dry Weight ug/L) Data—October 24-25, 2007

	RM	Date	Time	Total Zoo Density	Total Zoo Biomass	Rotifer Density	Rotifer Biomass	Copepod Density	Copepod Mass	Cladoceran Density	Cladoceran Biomass	Ciliate Density
High-High Tide, Night	34	10/24/2007	18:00	173.3	30.46	105.00	2.14	66.67	27.65	1.67	0.68	21.7
	36	10/24/2007	18:25	295.0	36.68	216.67	5.34	78.33	31.33	0.00	0.00	16.7
	38	10/24/2007	18:37	458.3	59.95	341.67	11.95	113.33	44.91	3.33	3.08	45.0
	40	10/24/2007	19:01	218.3	33.8	145.00	3.53	71.67	28.91	1.67	1.41	16.7
	42	10/24/2007	19:14	50.0	8.2	30.00	0.23	20.00	8.00	0.00	0.00	5.0
	46	10/24/2007	19:41	101.7	23.2	46.67	1.20	55.00	22.00	0.00	0.00	8.3
	50	10/24/2007	20:21	78.3	9.4	58.33	1.39	20.00	8.00	0.00	0.00	3.3
	54	10/24/2007	20:44	41.7	3.2	35.00	0.57	6.67	2.67	0.00	0.00	8.3
	56.8	10/24/2007	21:00	30.0	0.9	28.33	0.22	1.67	0.67	0.00	0.00	0.0
Low-Low Tide, Day	34	10/25/2007	8:35	105.0	17.4	68.33	1.11	36.67	16.25	0.00	0.00	8.3
	36	10/25/2007	9:00	228.3	19.5	188.33	3.38	36.67	14.56	3.33	1.58	20.0
	38	10/25/2007	9:20	220.0	19.5	188.33	6.95	30.00	12.00	1.67	0.51	20.0
	40	10/25/2007	9:35	51.7	8.4	31.67	0.39	20.00	8.00	0.00	0.00	20.0
	42	10/25/2007	9:50	81.7	16.6	41.67	0.60	40.00	16.00	0.00	0.00	11.7
	46	10/25/2007	10:00	65.0	4.5	55.00	0.48	10.00	4.00	0.00	0.00	10.0
	50	10/25/2007	10:30	23.3	0.8	21.67	0.11	1.67	0.67	0.00	0.00	6.7
	54	10/25/2007	10:55	55.0	2.5	51.67	1.13	3.33	1.33	0.00	0.00	5.0
	56.8	10/25/2007	11:10	41.7	0.7	40.00	0.48	1.67	0.25	0.00	0.00	1.7

Table 10. Zooplankton Density (organisms/L) and Biomass (Dry Weight ug/L) Data—October 31–November 1, 2007

	RM	Date	Time	Total Zoo Density	Total Zoo Biomass	Rotifer Density	Rotifer Biomass	Copepod Density	Copepod Mass	Cladoceran Density	Cladoceran Biomass	Ciliate Density
High-High Tide, Night	32	10/31/2007	22:10	55.0	10.32	30.00	0.30	23.33	9.34	1.67	0.68	8.3
	34	10/31/2007	22:18	103.3	10.93	83.33	1.72	20.00	9.21	0.00	0.00	11.7
	36	10/31/2007	22:33	115.0	11.95	90.00	1.95	25.00	10.00	0.00	0.00	38.3
	38	10/31/2007	22:46	166.7	36.2	111.67	2.34	51.67	30.98	3.33	2.87	25.0
	40	10/31/2007	23:00	58.3	19.9	31.67	0.48	21.67	8.67	5.00	10.74	16.7
	42	10/31/2007	23:17	41.7	9.4	26.67	0.32	13.33	6.32	1.67	2.80	5.0
	46	10/31/2007	23:40	25.0	0.8	23.33	0.18	1.67	0.67	0.00	0.00	6.7
Low-Low Tide, Day	32	11/1/2007	11:00	118.3	24.9	70.00	1.23	48.33	23.65	0.00	0.00	3.3
	34	11/1/2007	10:50	123.3	20.4	95.00	1.69	28.33	18.72	0.00	0.00	26.7
	36	11/1/2007	10:26	110.0	26.3	60.00	0.66	48.33	24.48	1.67	1.19	6.7
	38	11/1/2007	10:00	93.3	11.2	71.67	2.54	21.67	8.67	0.00	0.00	8.3
	40	11/1/2007	9:45	60.0	4.4	50.00	0.40	10.00	4.00	0.00	0.00	5.0
	42	11/1/2007	9:25	30.0	9.5	23.33	0.79	6.67	8.72	0.00	0.00	3.3
	46	11/1/2007	9:00	30.0	4.2	20.00	0.15	10.00	4.00	0.00	0.00	1.7
	50	11/1/2007	8:40	26.7	1.3	25.00	0.62	1.67	0.67	0.00	0.00	1.7
	54	11/1/2007	7:50	23.3	2.9	16.67	0.23	6.67	2.67	0.00	0.00	0.0

Table 11. Zooplankton Density (organisms/L) and Biomass (Dry Weight ug/L) Data—November 15, 2007

	RM	Date	Time	Total Zoo Density	Total Zoo Biomass	Rotifer Density	Rotifer Biomass	Copepod Density	Copepod Mass	Cladoceran Density	Cladoceran Biomass	Ciliate Density
High-High Tide, Night	32	11/15/2007	7:15	26.7	13.22	0.00	0.00	26.67	13.22	0.00	0.00	1.7
	34	11/15/2007	7:30	40.0	22.86	3.33	0.02	35.00	20.05	1.67	2.80	1.7
	36	11/15/2007	8:00	25.0	9.48	3.33	0.12	21.67	9.36	0.00	0.00	0.0
	38	11/15/2007	8:30	43.3	4.0	36.67	1.14	6.67	2.87	0.00	0.00	6.7
	40	11/15/2007	8:40	38.3	13.0	18.33	1.43	18.33	10.57	1.67	1.00	8.3
	42	11/15/2007	8:50	11.7	3.0	6.67	0.44	5.00	2.59	0.00	0.00	3.3
	46	11/15/2007	9:10	20.0	2.8	11.67	0.13	8.33	2.65	0.00	0.00	8.3
	50	11/15/2007	9:30	8.3	1.4	5.00	0.03	3.33	1.33	0.00	0.00	3.3
	54	11/15/2007	9:55	10.0	1.5	6.67	0.15	3.33	1.33	0.00	0.00	3.3
	56.8	11/15/2007	10:15	25.0	2.5	20.00	0.95	5.00	1.58	0.00	0.00	5.0
Low-Low Tide, Day	32	11/15/2007	19:45	13.3	7.1	0.00	0.00	13.33	7.09	0.00	0.00	8.3
	34	11/15/2007	20:00	21.7	23.9	1.67	0.00	16.67	8.72	3.33	15.18	6.7
	36	11/15/2007	20:10	16.7	11.4	0.00	0.00	16.67	11.43	0.00	0.00	5.0
	38	11/15/2007	20:25	66.7	26.4	20.00	0.10	41.67	20.78	5.00	5.51	1.7
	40	11/15/2007	20:38	58.3	15.5	30.00	0.51	26.67	14.12	1.67	0.86	5.0
	42	11/15/2007	20:50	41.7	9.2	26.67	0.48	15.00	8.72	0.00	0.00	6.7
	46	11/15/2007	21:10	18.3	21.3	5.00	0.10	13.33	21.24	0.00	0.00	1.7
	50	11/15/2007	21:25	11.7	12.7	3.33	0.09	8.33	12.63	0.00	0.00	6.7
	54	11/15/2007	22:00	26.7	3.8	18.33	0.43	8.33	3.33	0.00	0.00	3.3
	56.8	11/15/2007	22:05	23.3	7.9	18.33	0.31	5.00	7.55	0.00	0.00	3.3

Chapter 3
Conclusions

A longitudinal water quality monitoring investigation was performed on the San Joaquin River from Mossdale Crossing to Turner Cut to assess the benefit of installing the HORB. The study attempted to answer four questions.

1. What is the effect on flow of installing the HORB?
2. What is the effect on DO in the DWSC and SJR of installing and removing the HORB?
3. Are impacts to the SJR and DWSC beneficial or harmful?
4. Can the tracking of the installation add or provide information valuable to triggering use of the aeration facility?

Specific responses to these questions are provided in the Executive Summary.

In summary, the study determined that the installation of the HORB in 2007 altered the flow fraction continuing to the DWSC to 70 to 90% of the upstream flow. Flows to the DWSC were augmented with EWA reservoir releases to create a pulse of high flow during the HORB period. The combination of the pulse flow and the HORB caused DWSC flows to increase from about 500 cfs to a maximum of 1,900 cfs while the HORB was in place. Prior to the installation of the HORB only about 50% of the upstream flow remained in the San Joaquin River, the remaining flow entered Old River. The HOR flow is generally described with a simple equation: 50% SJR Vernalis plus 5% of the export pumping. After the HORB was removed in November 2007, this fraction decreased to less than expected (approximately 10%) from the general flow split relationship. It is not known why the percentage dropped after the removal. Export pumping was significant during the study period, but it cannot account for the decline in the flow fraction entering the DWSC. Possible explanations for this flow split reduction might be explained by pumping in the South Delta, removal of the South Delta Barriers on Grant Line or Old River days before the HORB was breached, or the deepening of Old River when the rock barrier was excavated. Additional analysis is required to isolate the cause in the flow split reduction.

The installation of the HORB and the associated EWA augmentation flows reduced the DO deficit in the DWSC above Turner Cut. With the increased flow passing through the DWSC the location of the DO minimum developed farther downstream, and for two sampling runs below the Turner Cut, the downstream limit of the study. DO concentrations in the DWSC at higher flows were reduced by about 1 to 2 mg/L. When the HORB was removed, the DWSC flows were again low and DO concentrations decreased in the DWSC, but remained at higher concentrations than observed prior to the barrier installation.

The overall effect on water quality during the flow pulse and HORB installation was to decrease travel (residence) time from Mossdale to the DWSC and in the DWSC to Turner Cut. The SJR water quality chemistry improved during the pulse flow. Conductivity, temperature, algae, and zooplankton concentrations all decreased as the flow increased. Zooplankton communities were transported farther downstream from Mossdale into the DWSC and were observed to decrease in both biomass concentration and diversity.

The BODs and water quality parameters suggest that it may be possible to develop a simple dynamic model to predict the response of DO in the DWSC to upstream changes in flow and water quality. It is recommended that effort be expended to better explore the development of this tool.

Chapter 4
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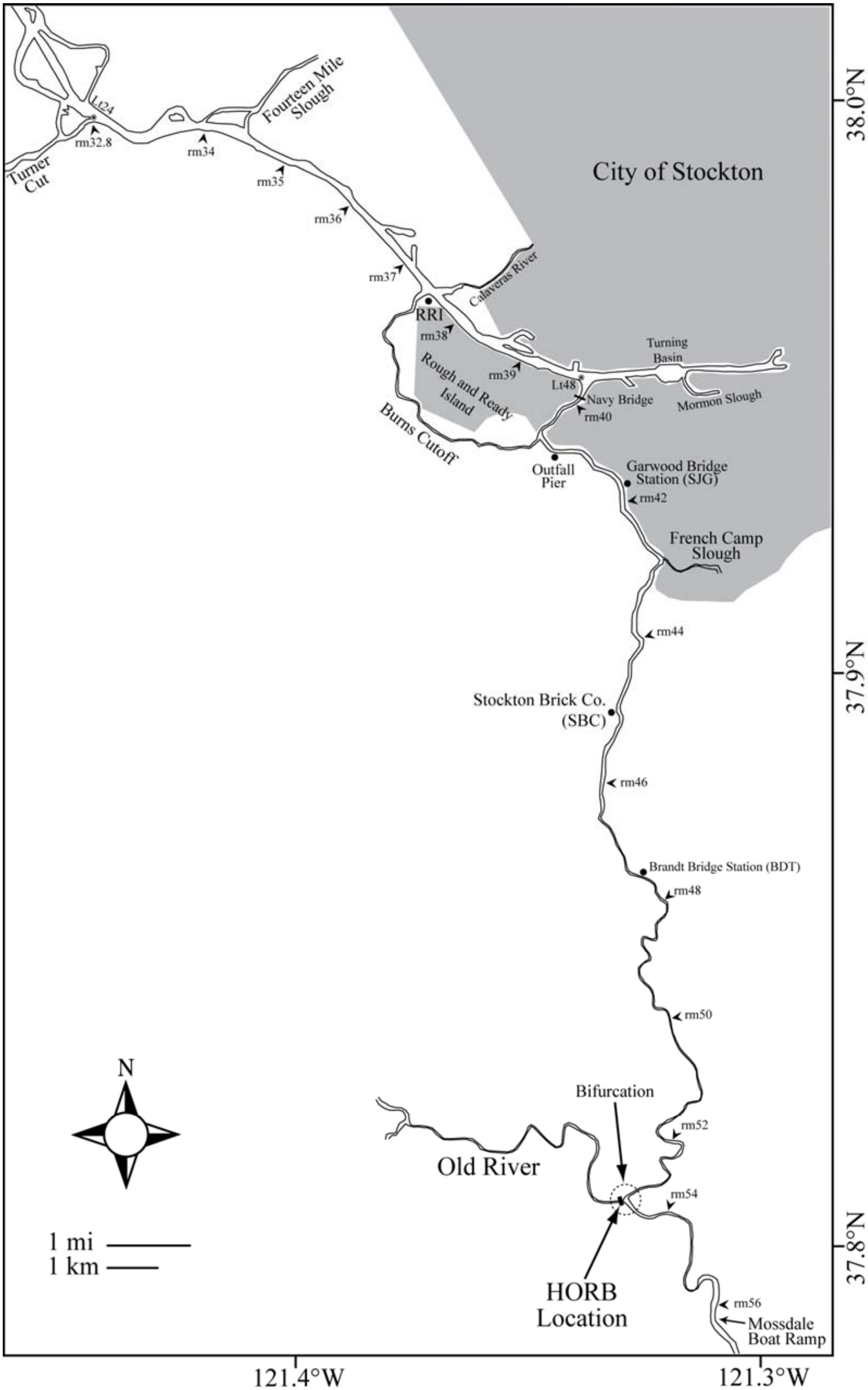

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Figure 1
Map of the Study Area: San Joaquin River, Mossdale Crossing to Turner Cut

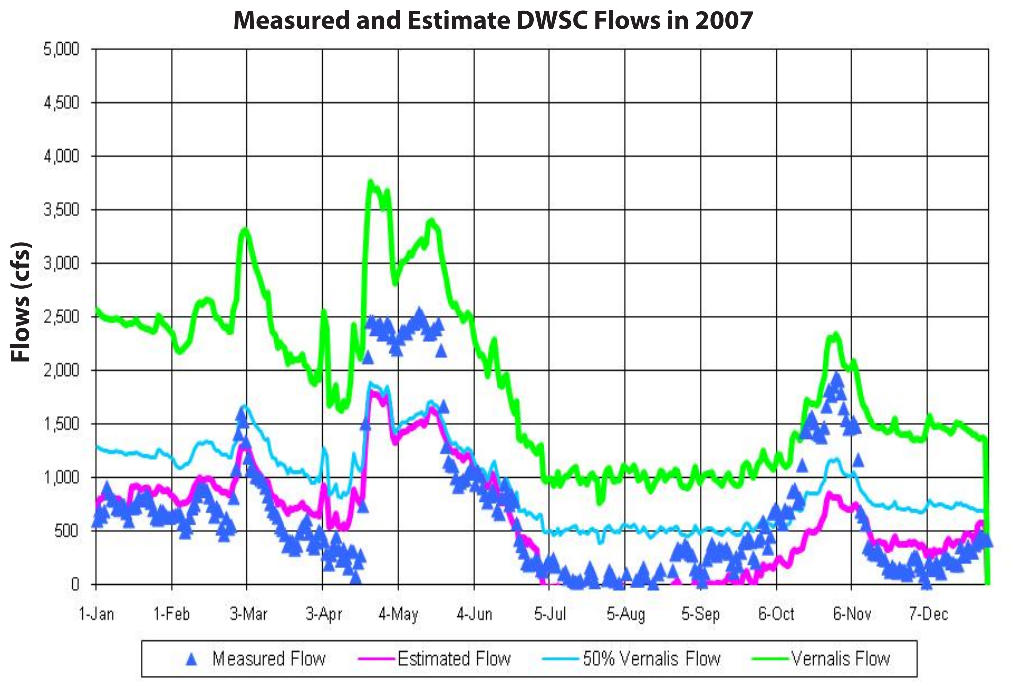

Figure 2: Flows entering the Study Area (Measured Flow is for the SJR at Garwood. Estimated Flow is Vernalis Less Old River Flows, Where Old River is Estimated by 50% Vernalis + 5% Export Flows.).

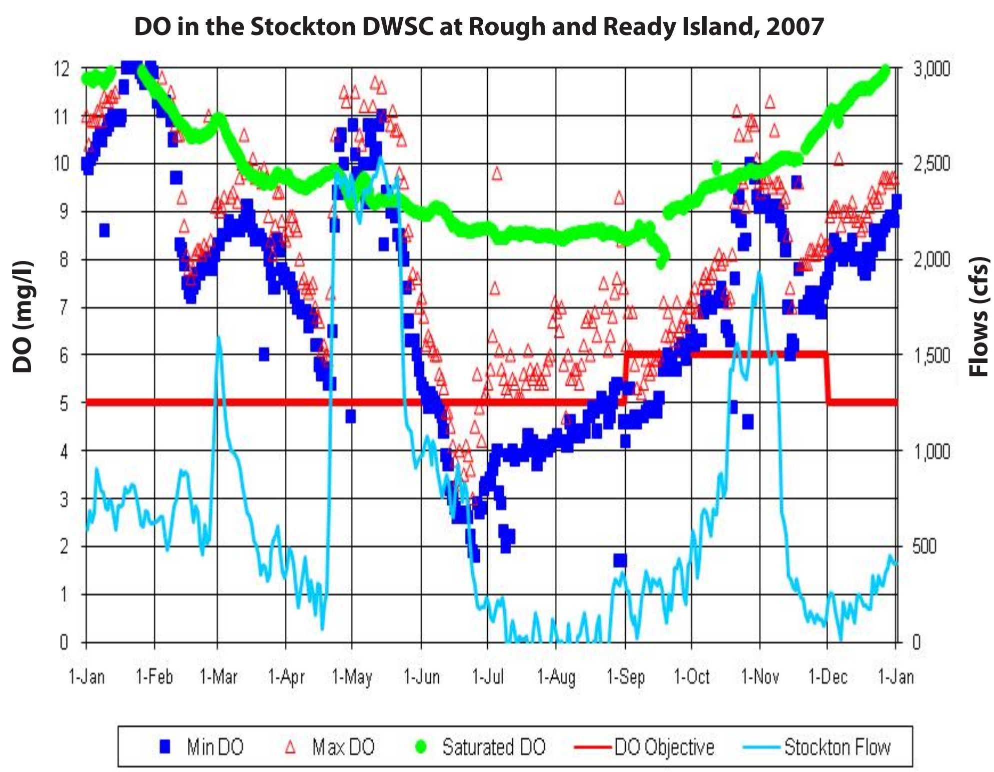

Figure 3: Dissolved Oxygen in the DWSC during 2007.

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Figure 2 and 3

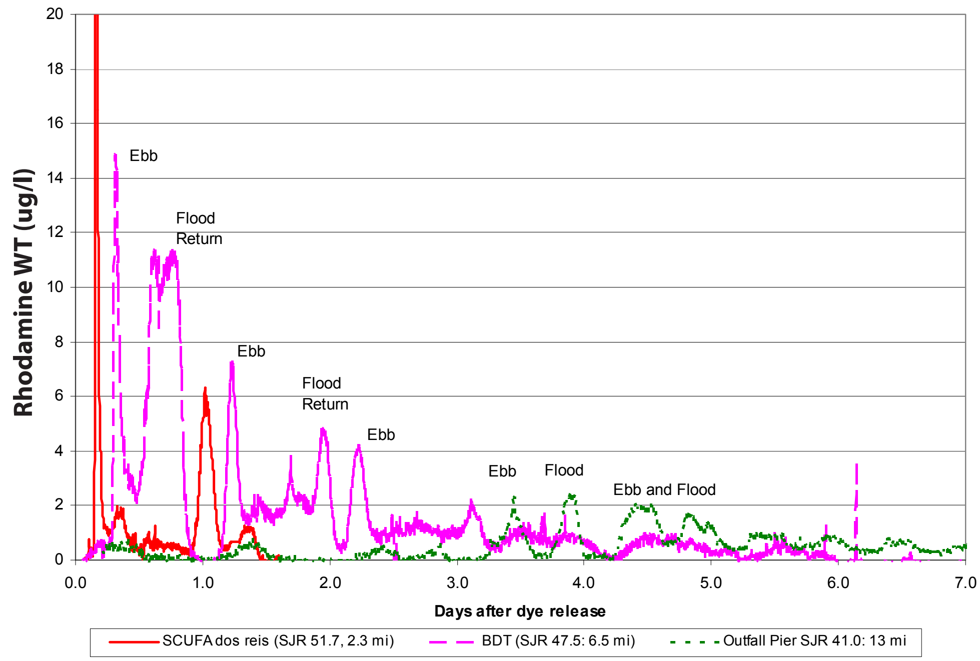

Figure 4: Rhodamine WT Tracer Profiles Released at the HORB on September 20, 2007 Passing Fixed Sensors at RM 51.1, RM 47.5, and RM 41.

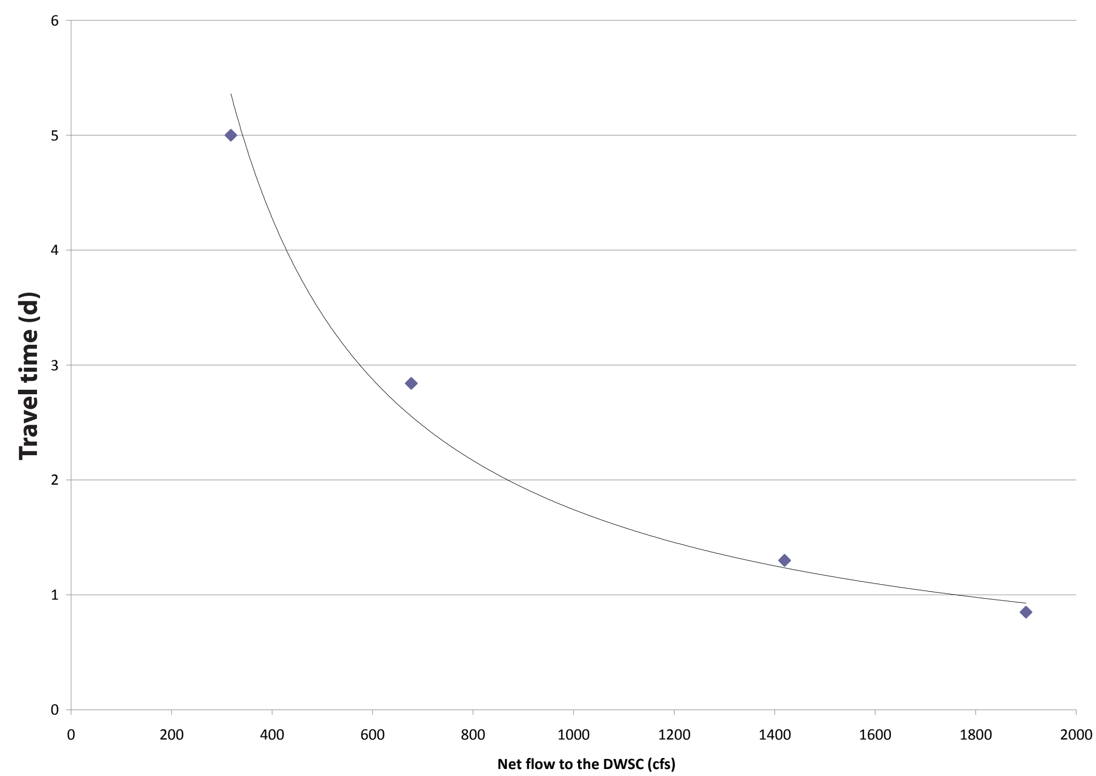

Figure 5: Residence Time from HORB to the DWSC as a Function of Net Flow into the DWSC.

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Figure 4 and 5

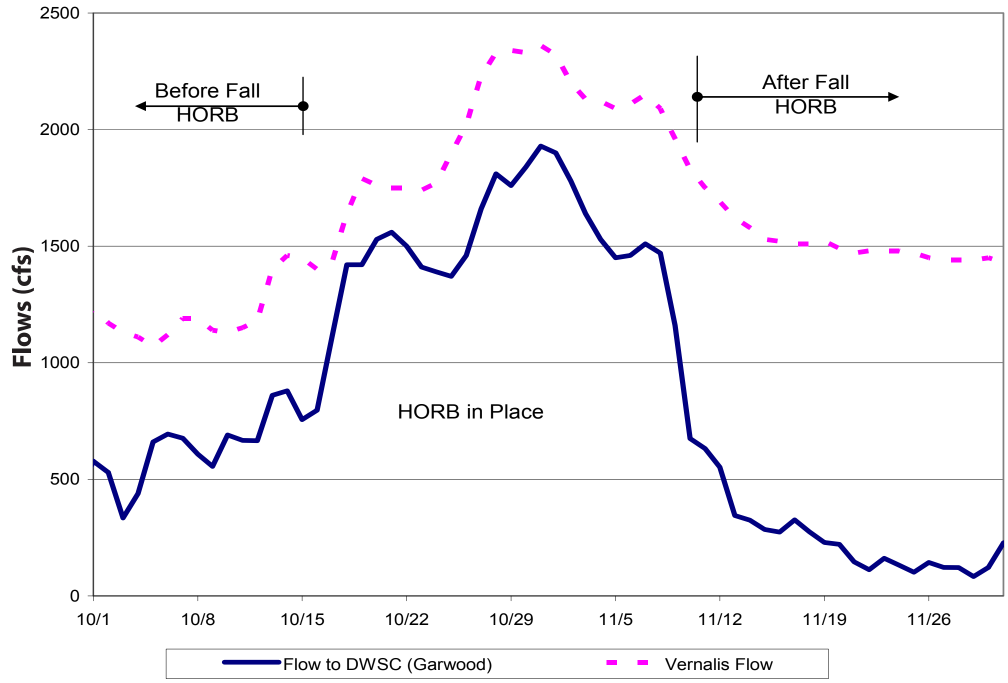

Figure 6: Flow at Vernalis and Net Flows entering the DWSC before, during, and after the HORB Installation.

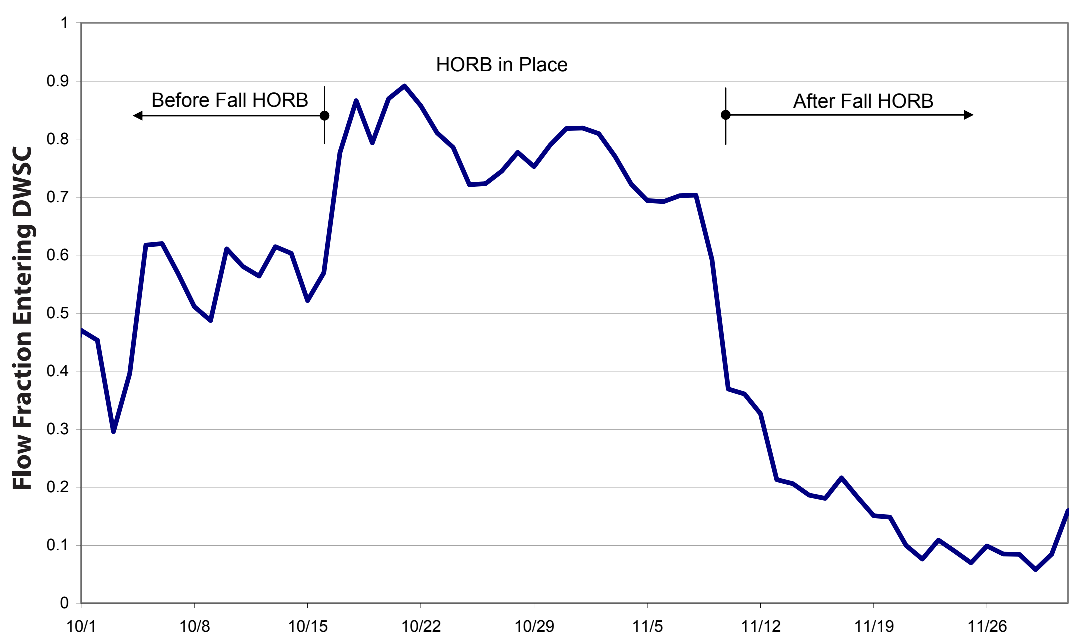

Figure 7: Fraction of the Vernalis Flow through the DWSC for October and November 2007.

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Figure 6 and 7

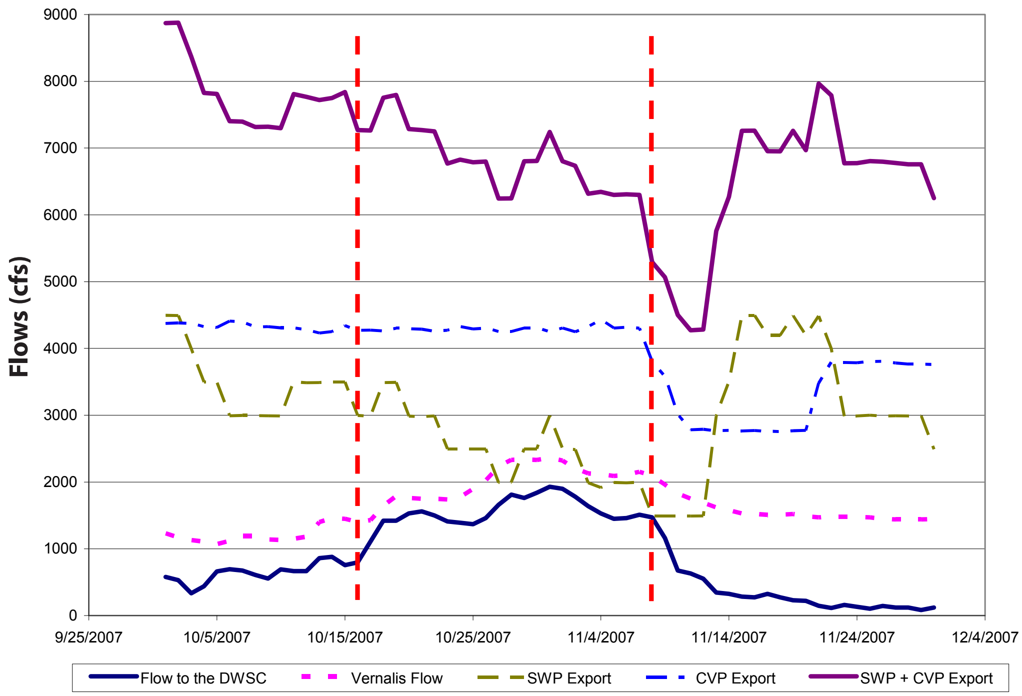

Figure 8: State Water Project and Central Valley Project Export Flows during the Fall 2007 HORB Period.

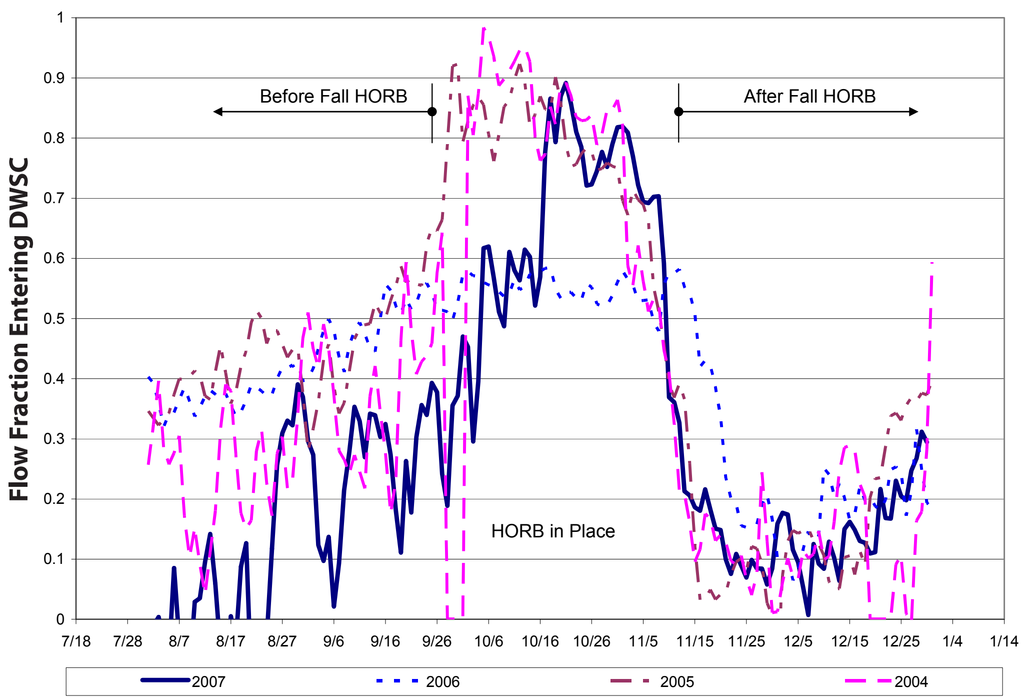

Figure 9: Flow Fraction entering the DWSC Relative to Vernalis 2004–2007.

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Figure 8 and 9

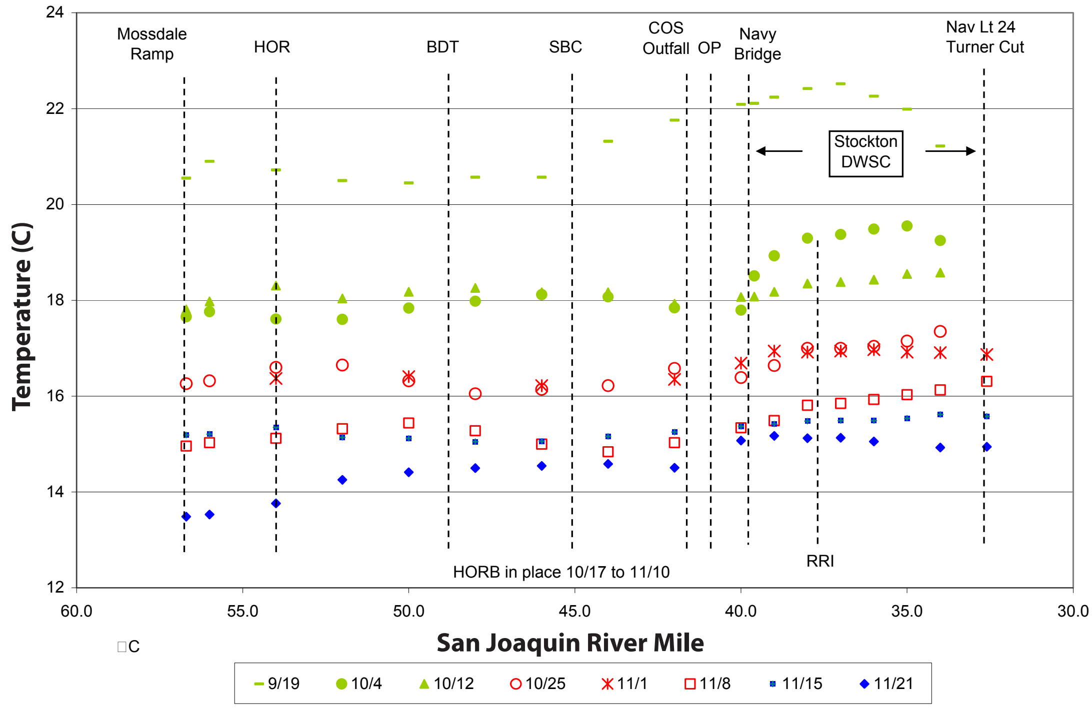

Figure 10: Longitudinal Water Temperature Profiles before, during, and after the HORB Installation

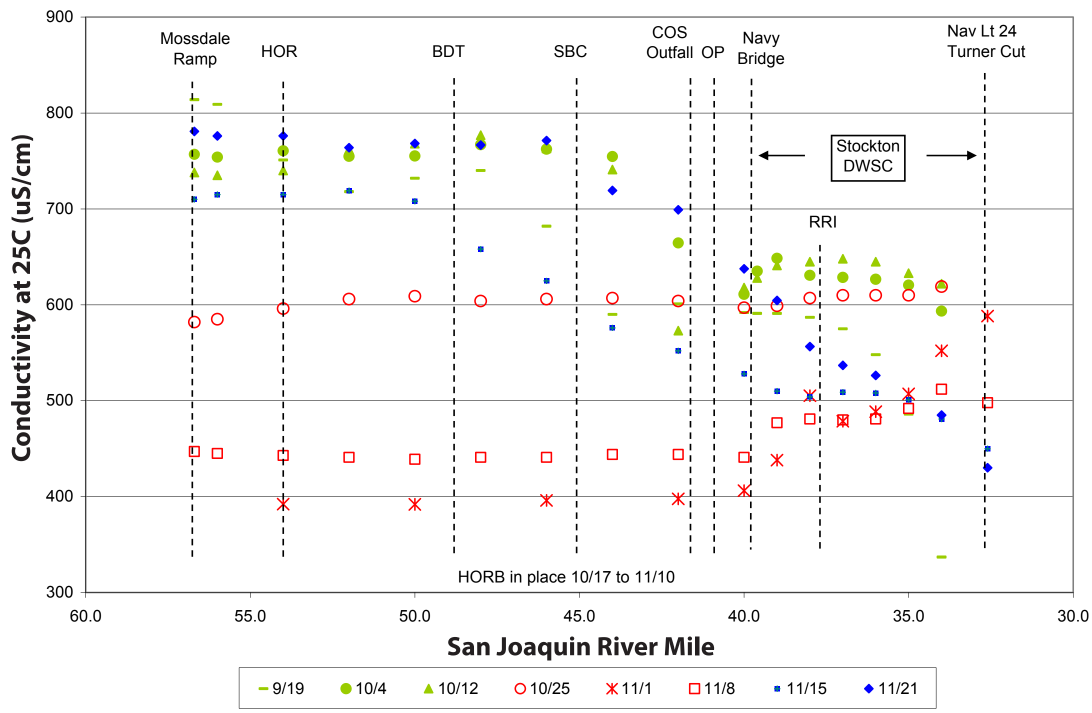

Figure 11: Longitudinal Electrical Conductivities before, during, and after the HORB Installation.

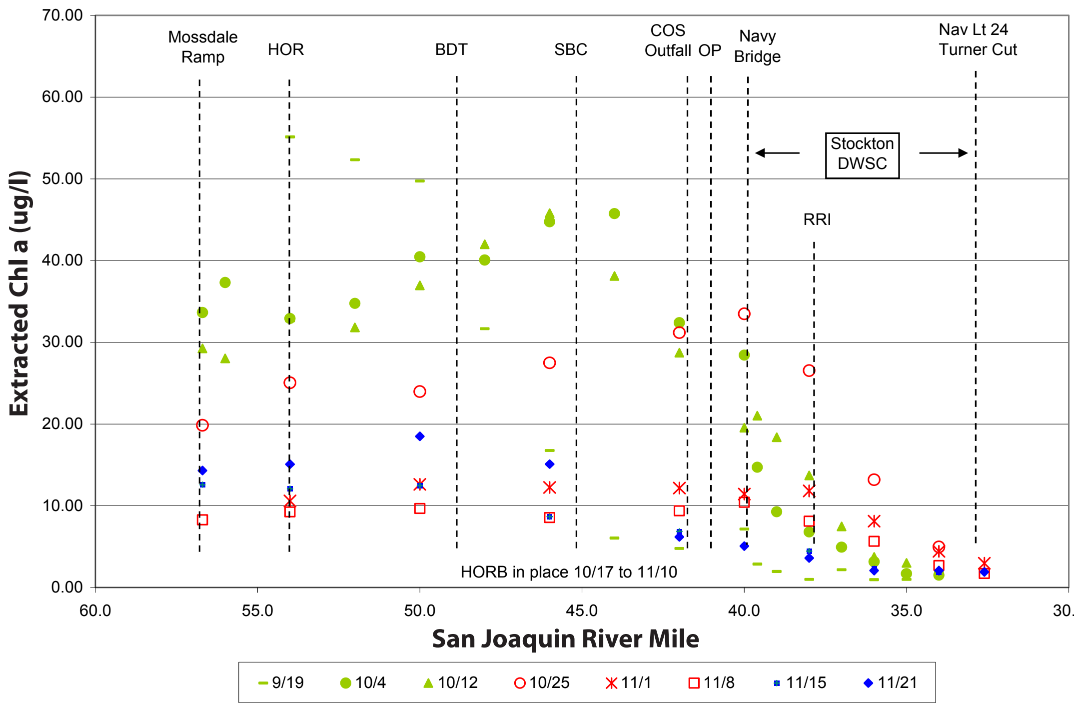

Figure 12: Longitudinal Extracted Chlorophyll A Concentrations before, during, and after the HORB Installation.

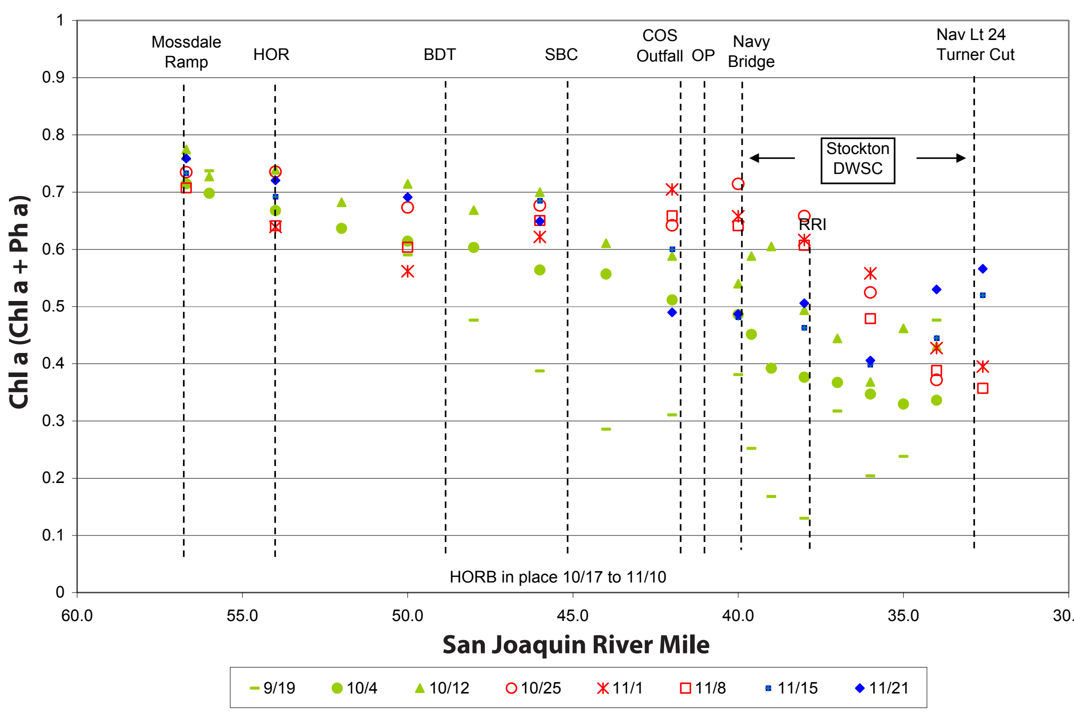

Figure 13: Fraction of Chlorophyll A to Chlorophyll A and Pheophytin A Pigment Concentrations.

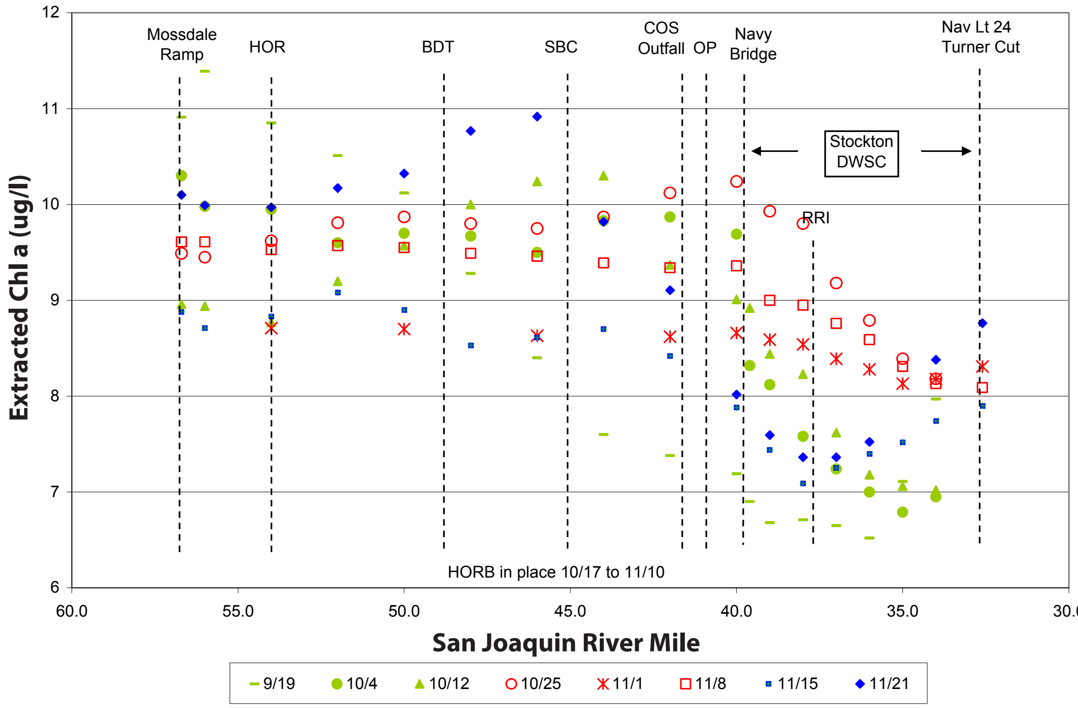

Figure 14: Longitudinal Dissolved Oxygen Concentrations from Mossdale to Turner Cut.

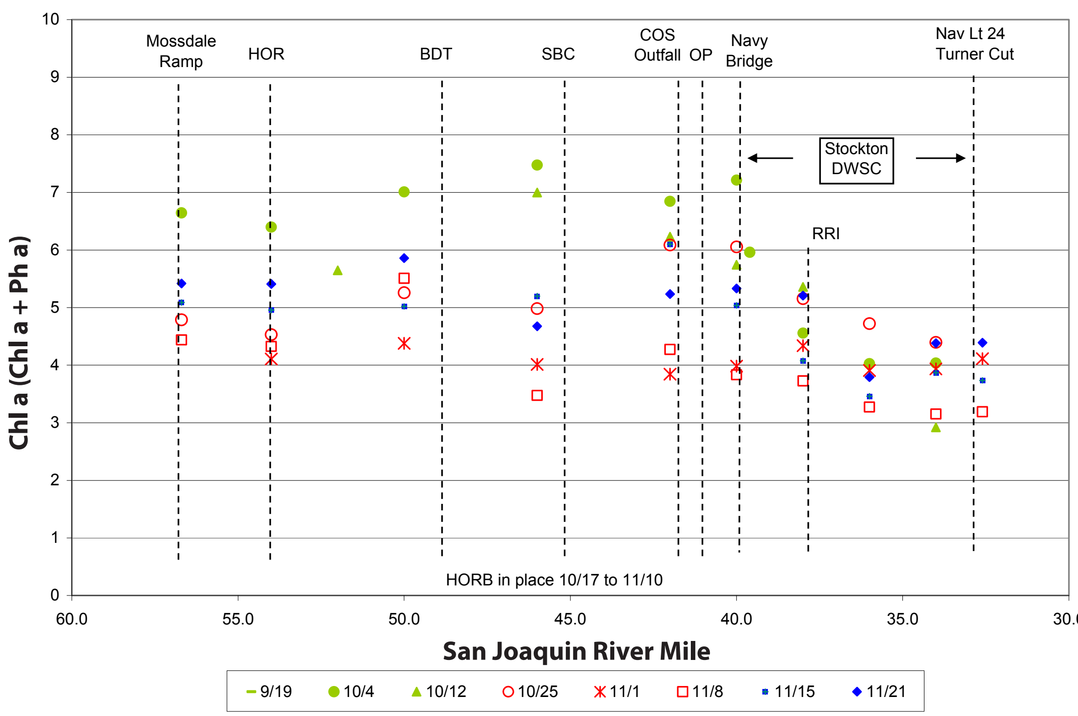

Figure 15: Longitudinal Ultimate Biochemical Oxygen Demands before, during, and after the HORB.

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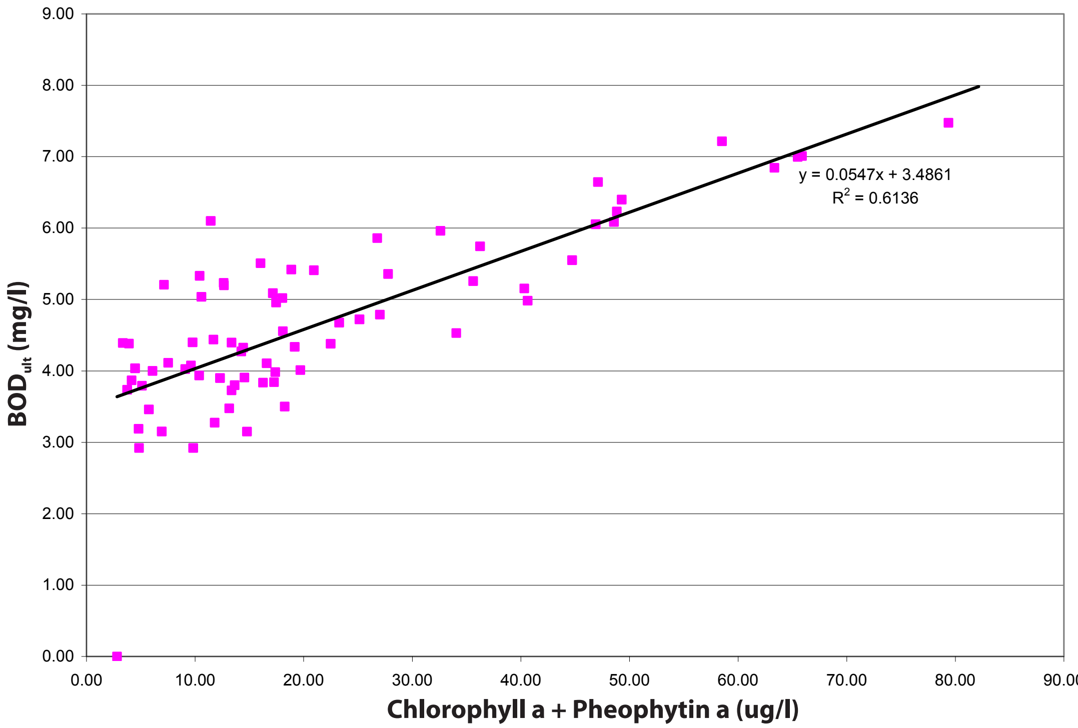

Figure 16: The Contribution of Algae to the Ultimate BOD Concentration during October and November 2007.

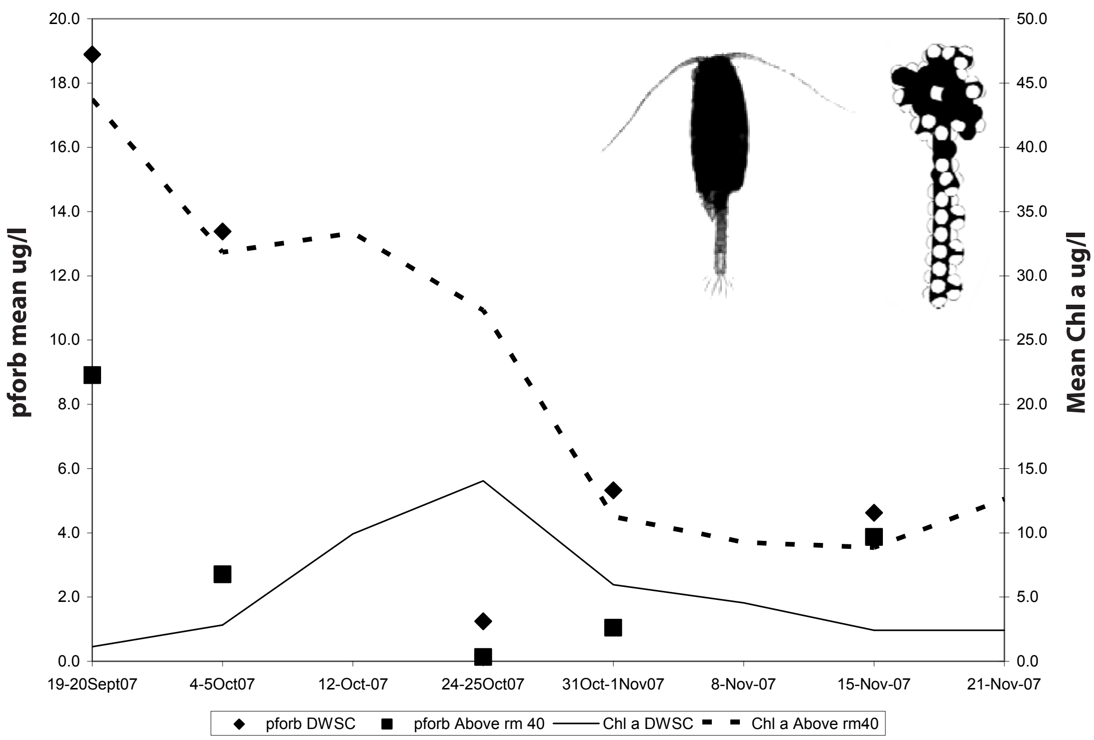

Figure 17: Changes in Biomass for the Copepod Pseudodiaptomus forbesi and Chlorophyll A .

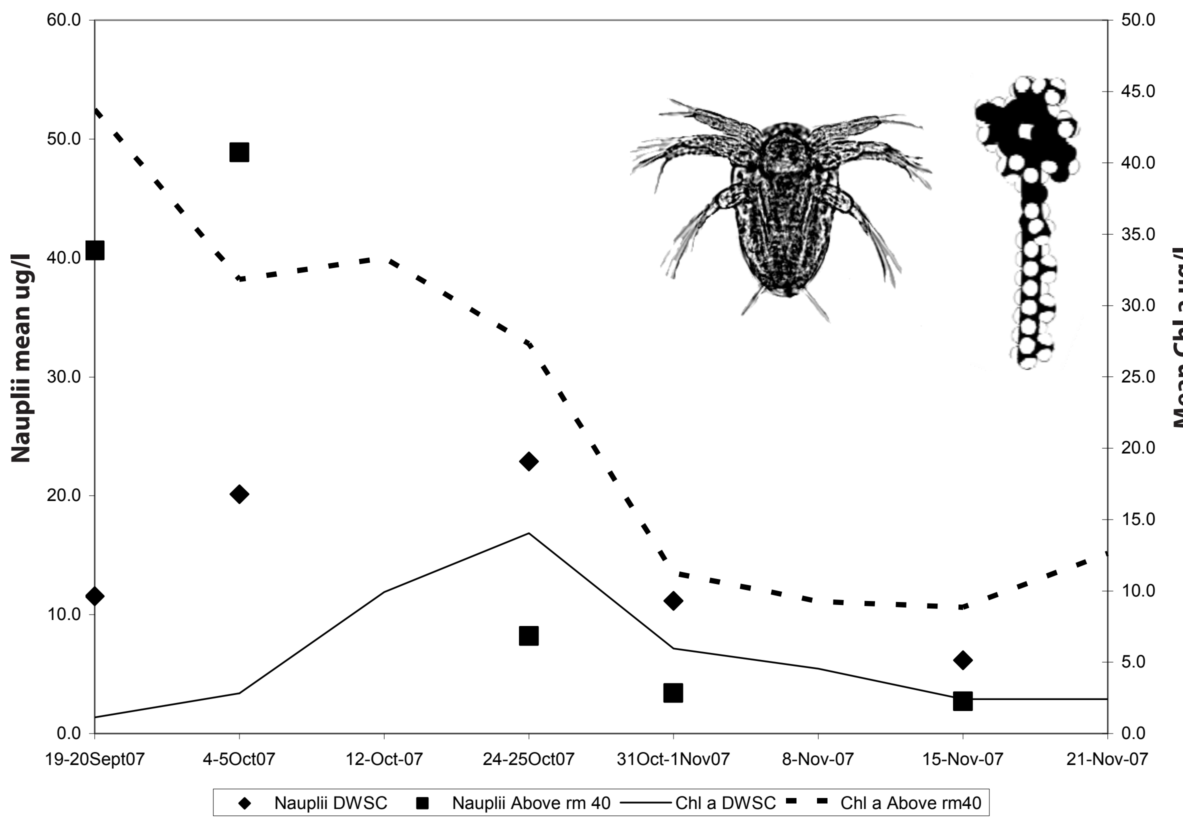

Figure 18: Changes in Biomass for Copepod nauplii and Concentration of Chlorophyll A.

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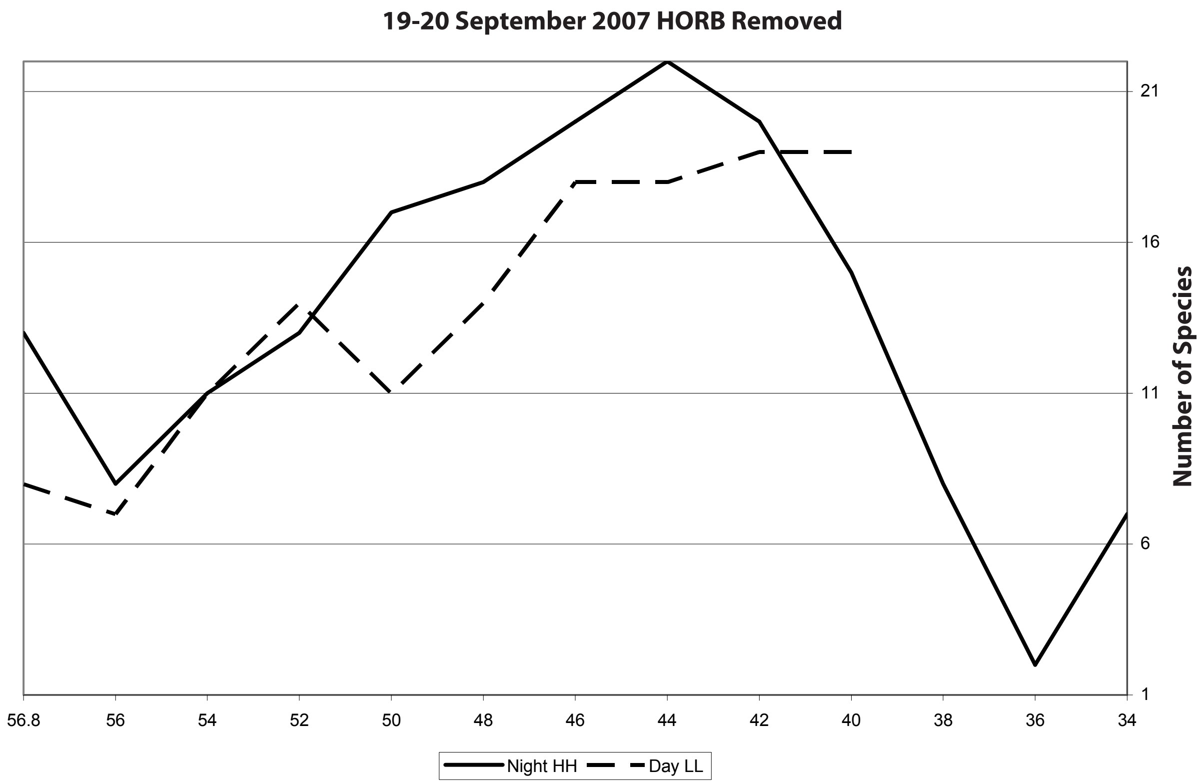

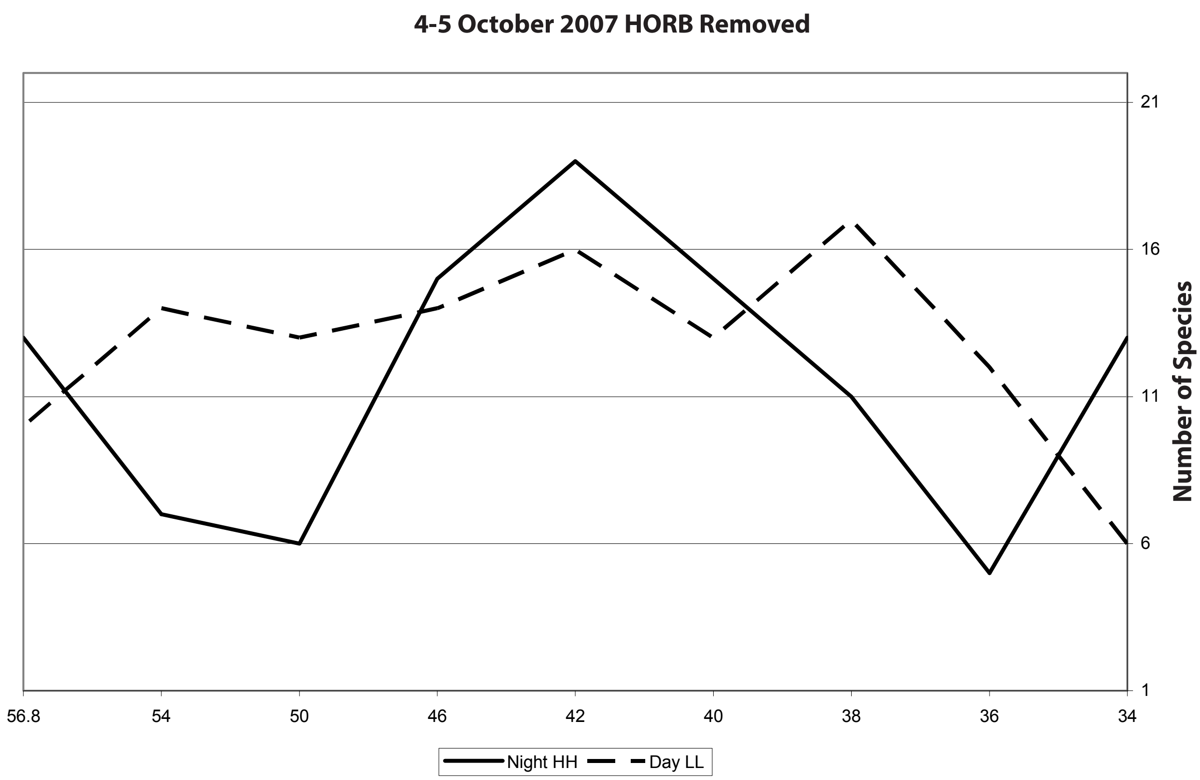

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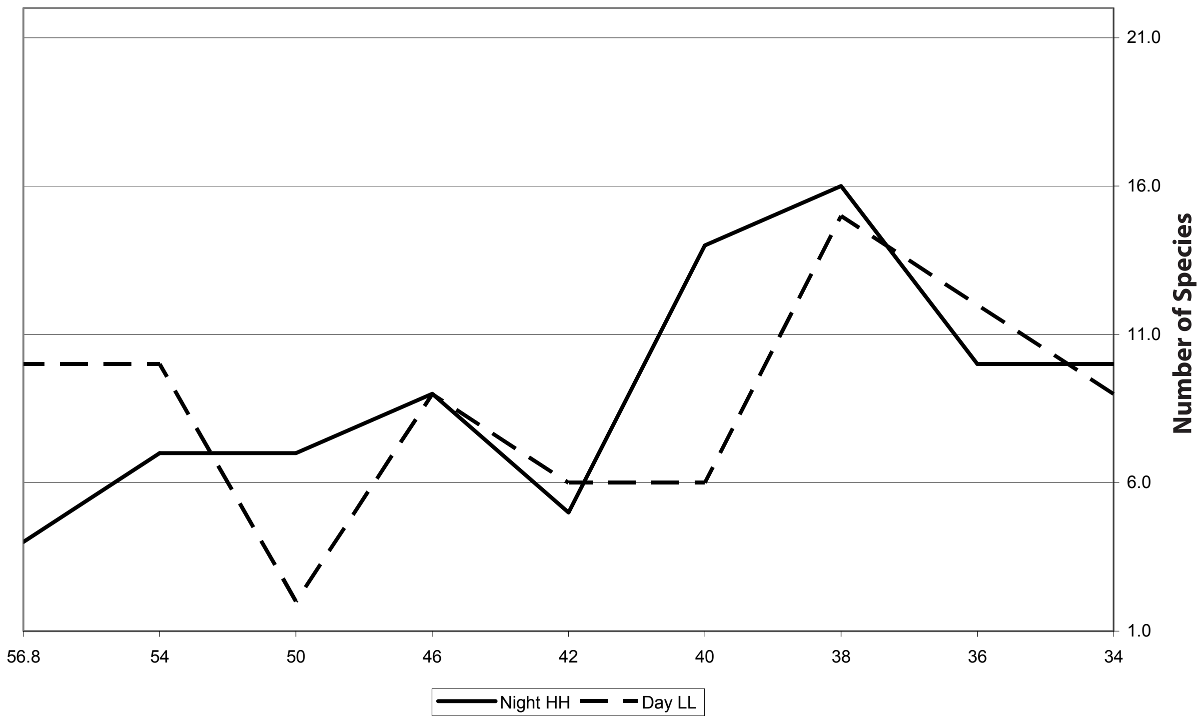
Figure 19
Overall Species Diversity Patterns from September 19–20 and October 4–5, 2007

24-25 October 2007 HORB Installed



31 October - 1 November 2007 in EWA flows

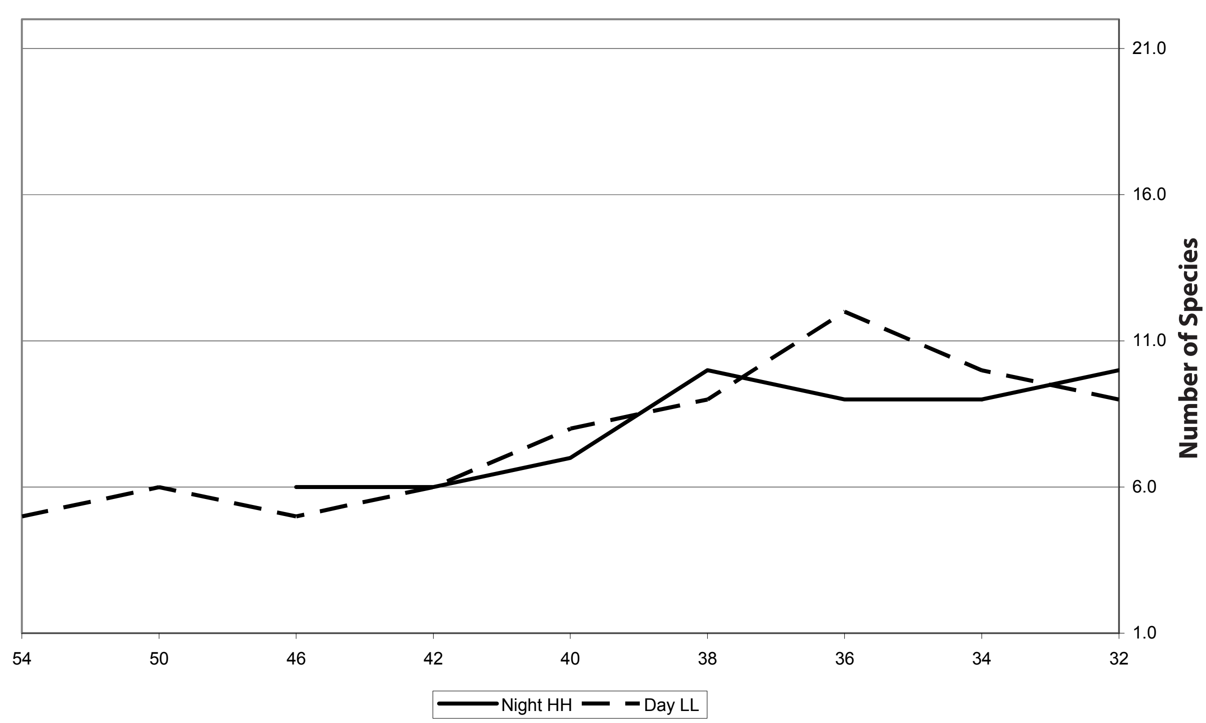


Figure 20
Overall Species Diversity Patterns for October 24–25 and October 31–November 1, 2007

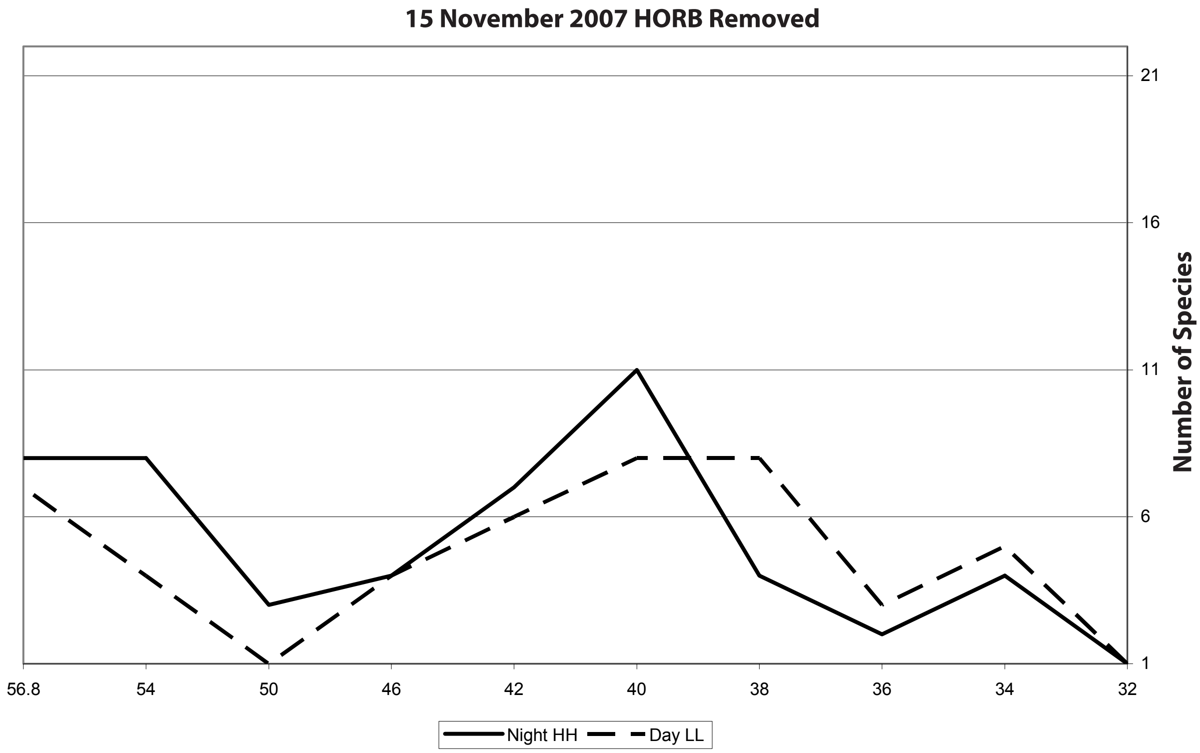


Figure 21: Overall Species Diversity Patterns for November 15, 2007.

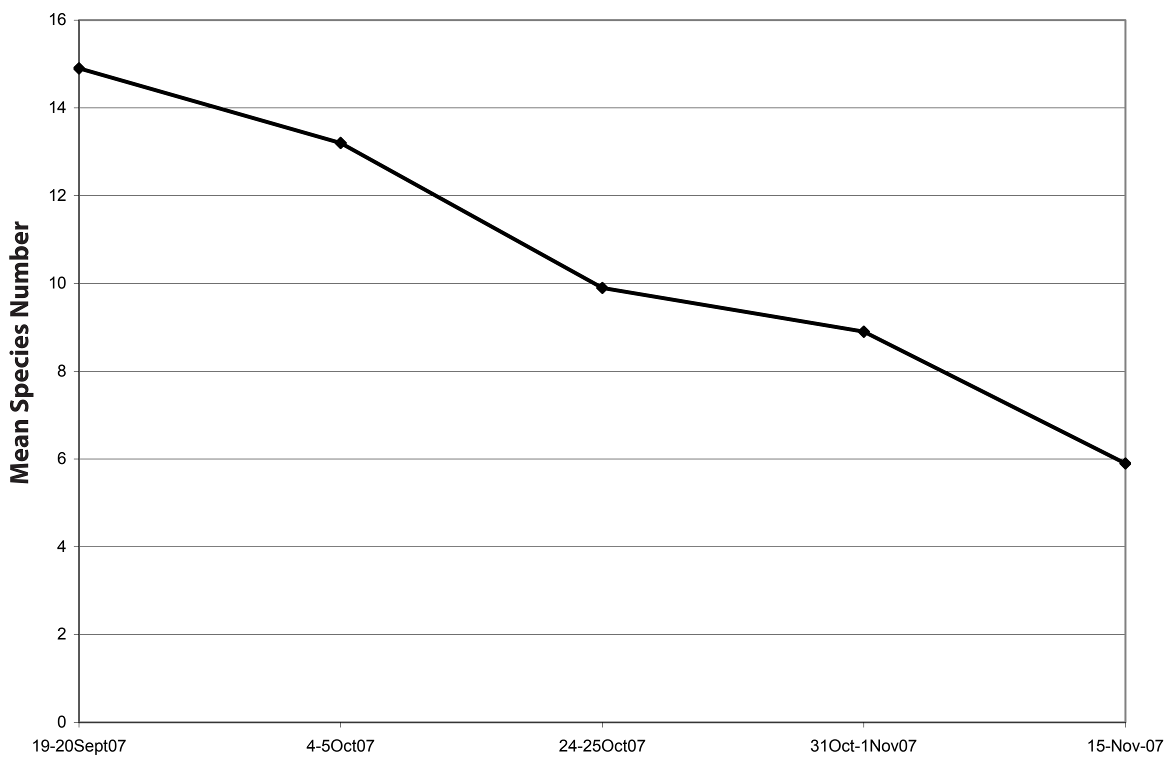
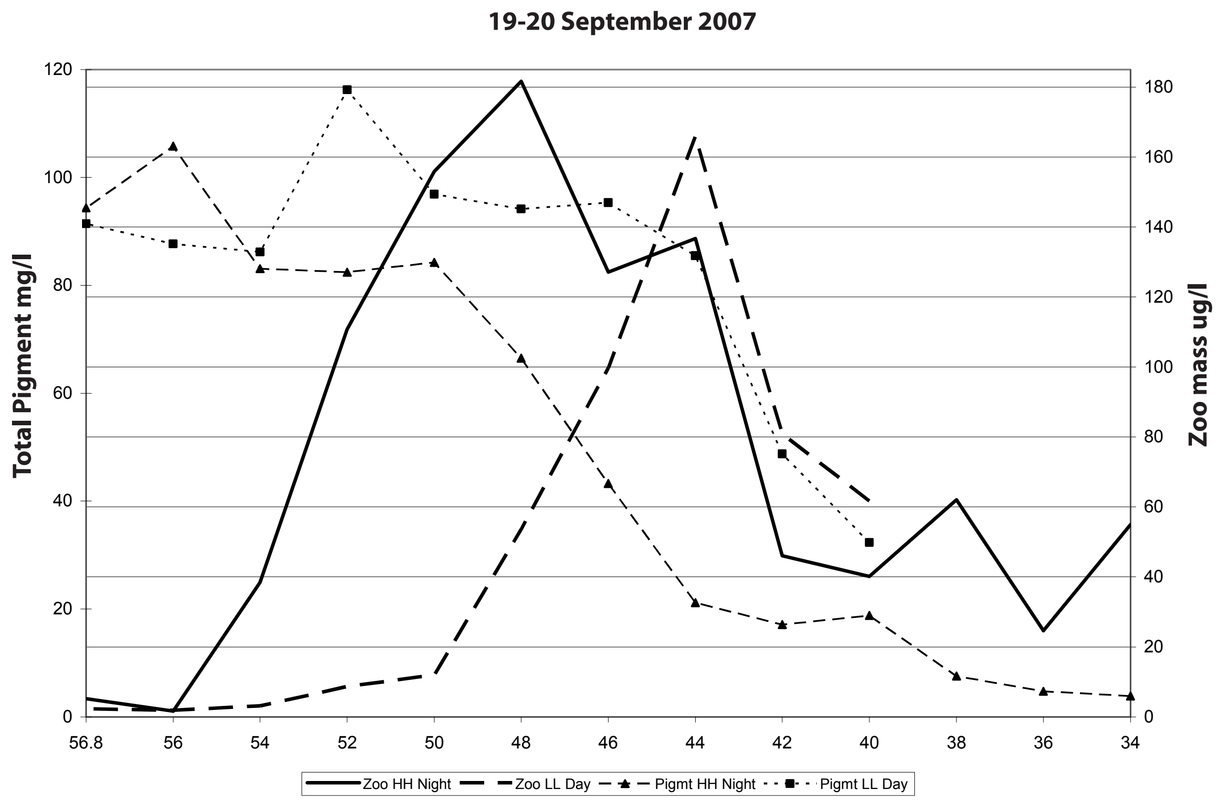


Figure 22: Changes in Species Diversity over All Sampling Periods (Mean Values Plotted).



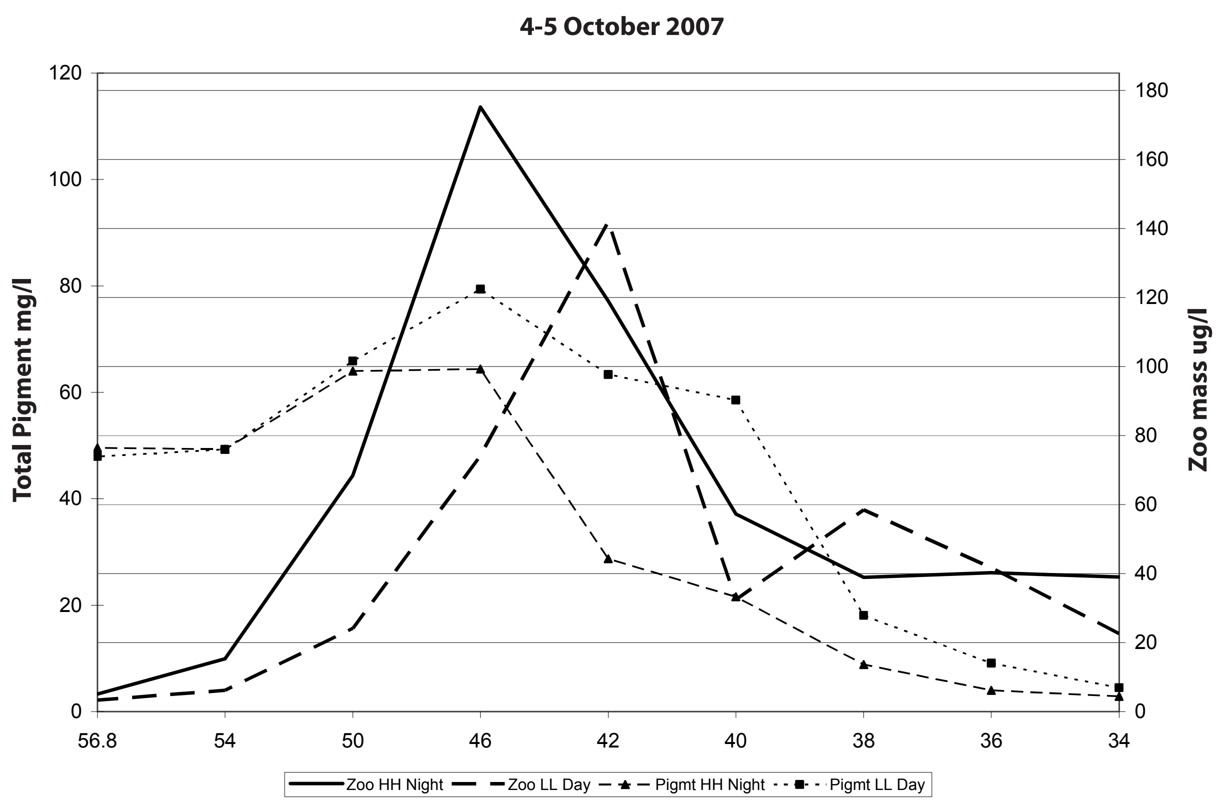


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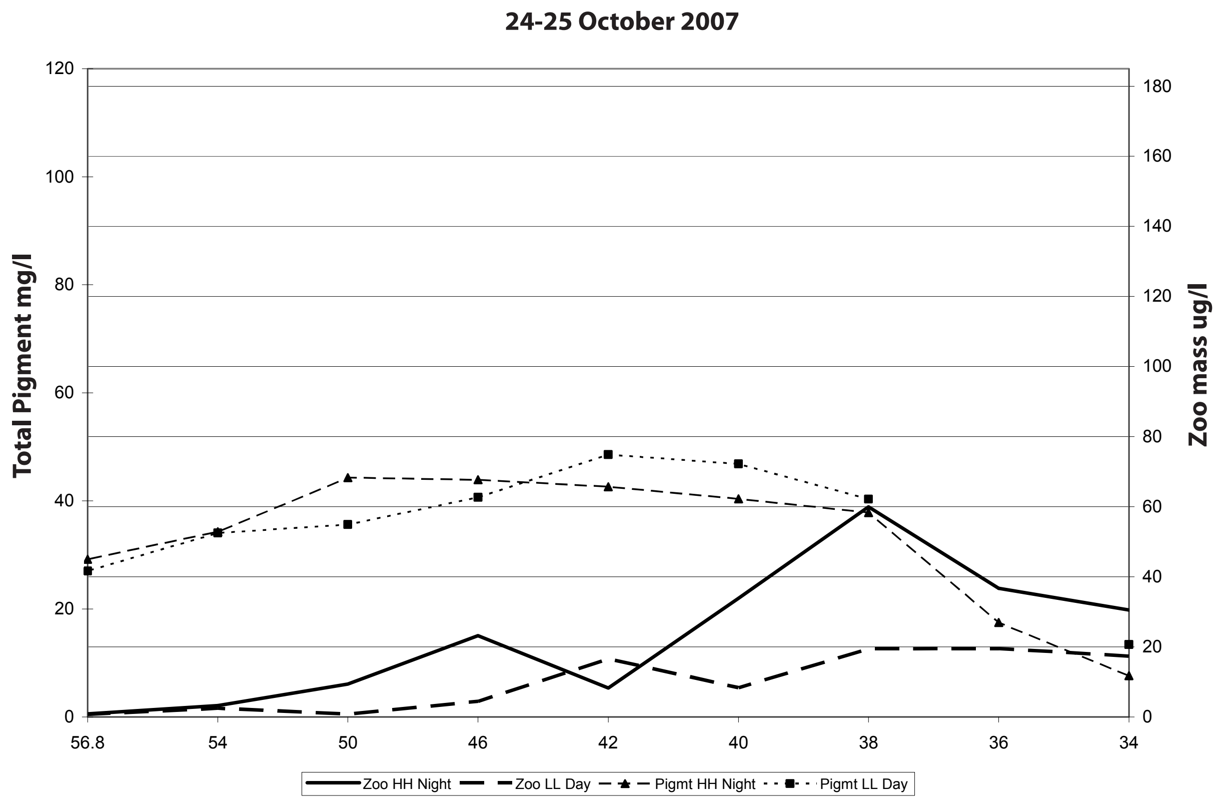
Figure 23
Zooplankton Biomass and Total Pigment for September 19–20 and October 4–5, 2007



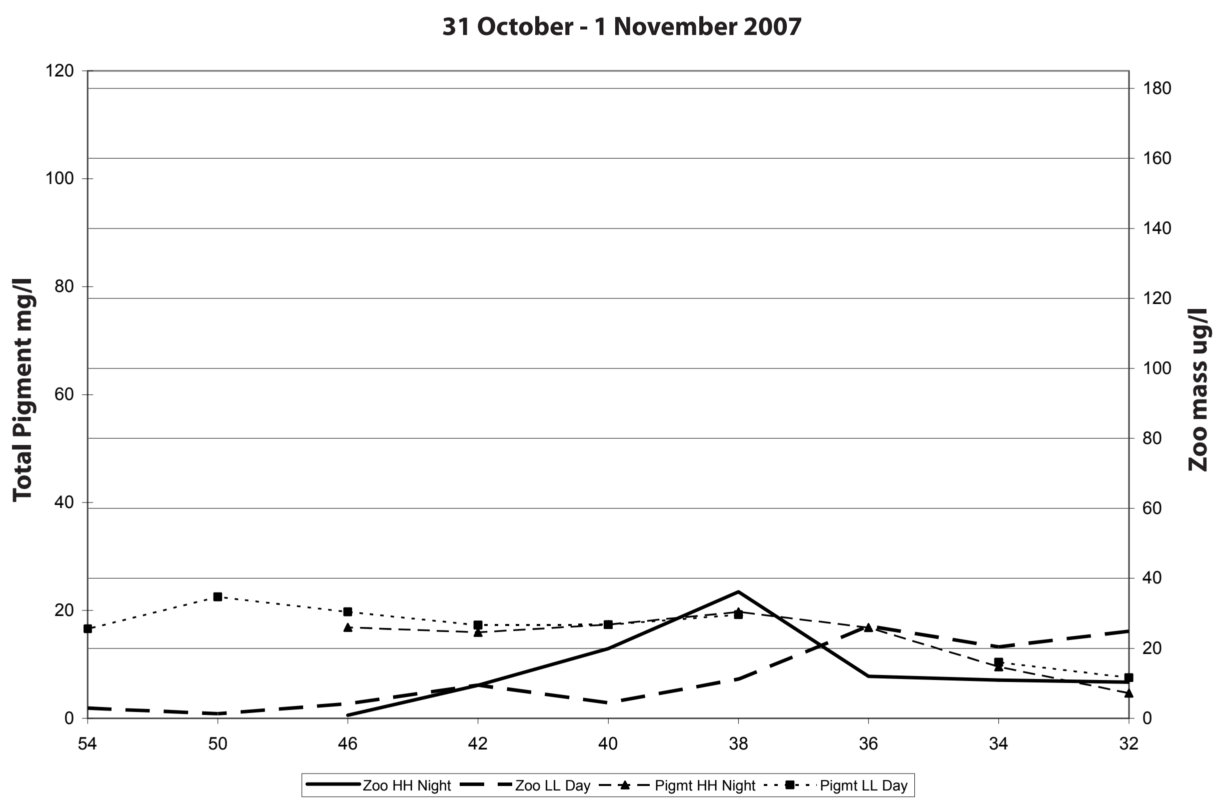


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Figure 24
Zooplankton Biomass and Total Pigment for October 24–25 and October 31–November 1, 2007

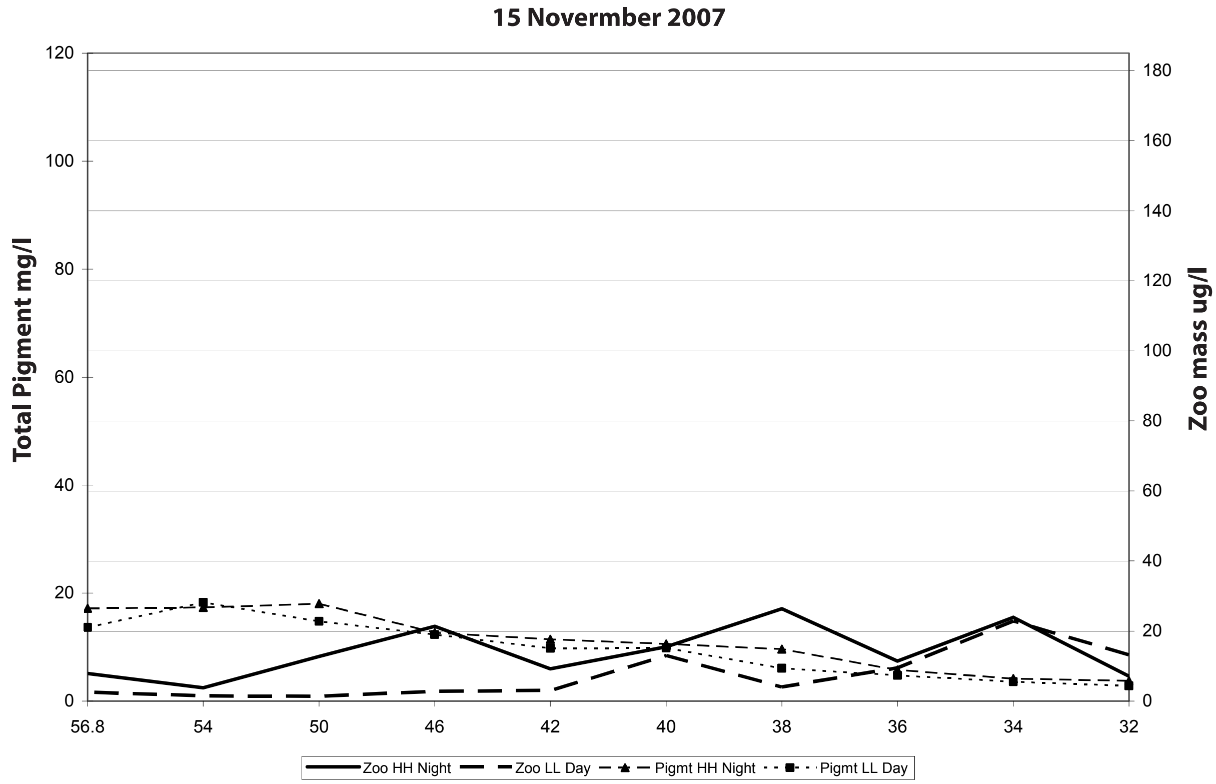

Figure 25: Zooplankton Biomass and Total Pigment for November 15, 2007.

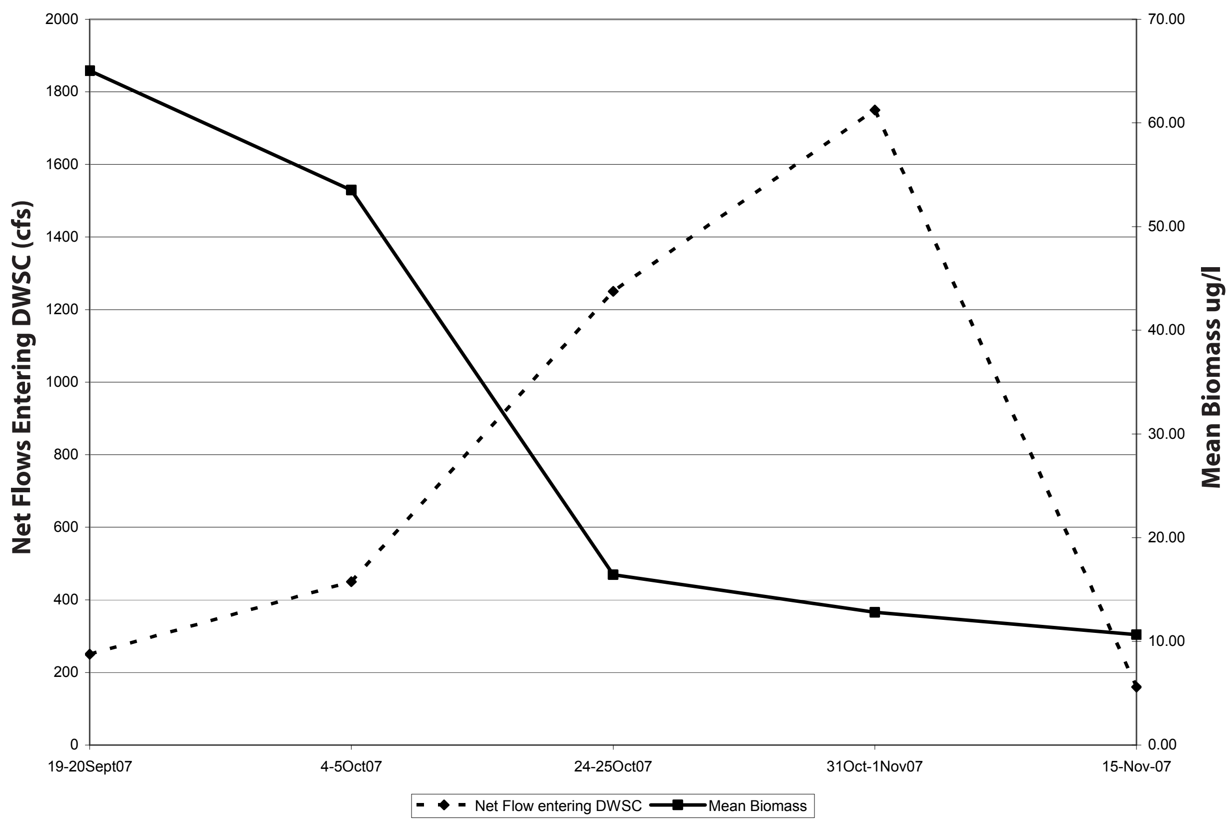

Figure 26: Change in Mean Biomass in relation to Flow for All Zooplankton Species over Sampling Periods.

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Figure 25 and 26

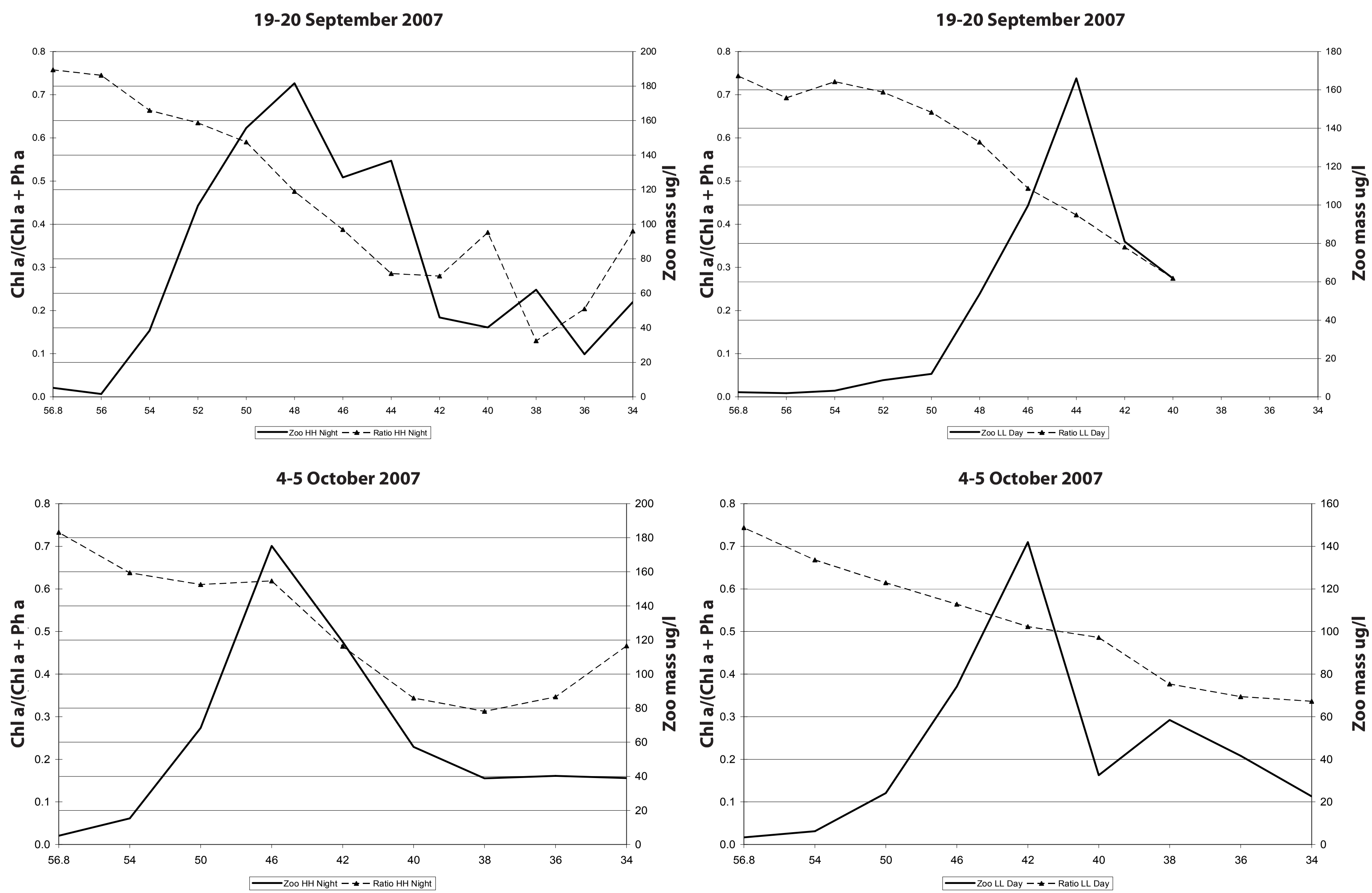

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Figure 27
Relationship between Total Zooplankton Biomass and Phytoplankton Pigment Ratio for September 19–20 and October 4–5, 2007

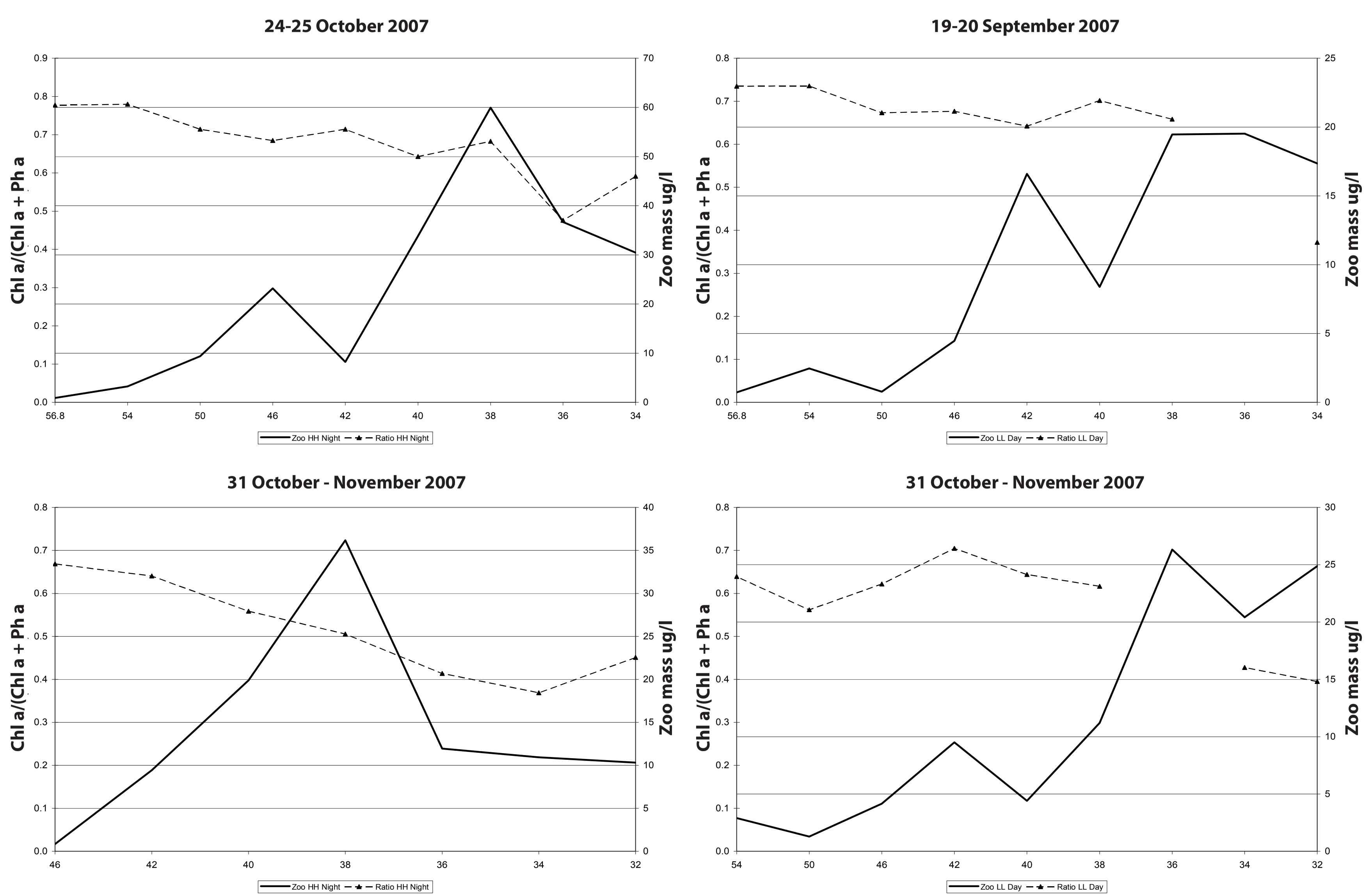

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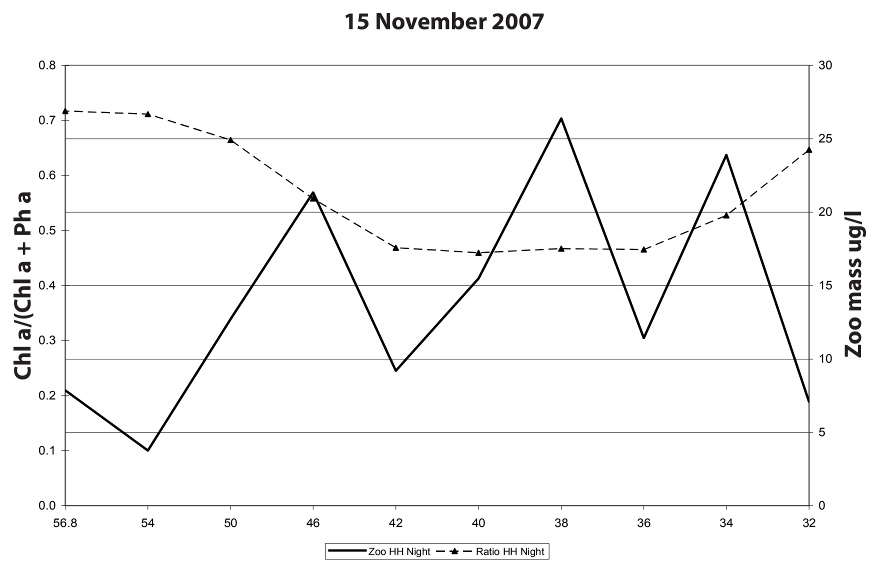
Figure 28
Relationship between Total Zooplankton Biomass and Phytoplankton Pigment Ratio for October 24–25 and October 31–November 1, 2007



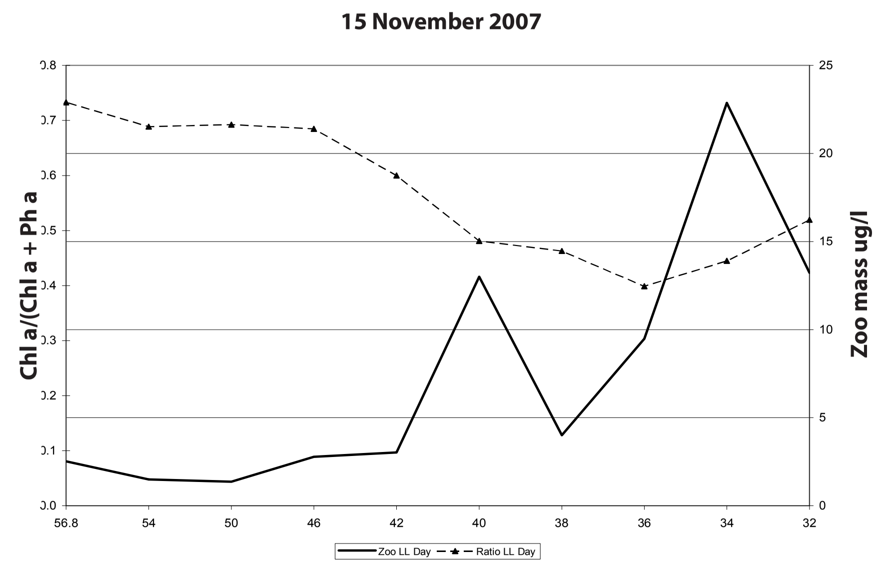


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Figure 29
Relationship between Total Zooplankton Biomass and Phytoplankton Pigment Ratio for November 15, 2007

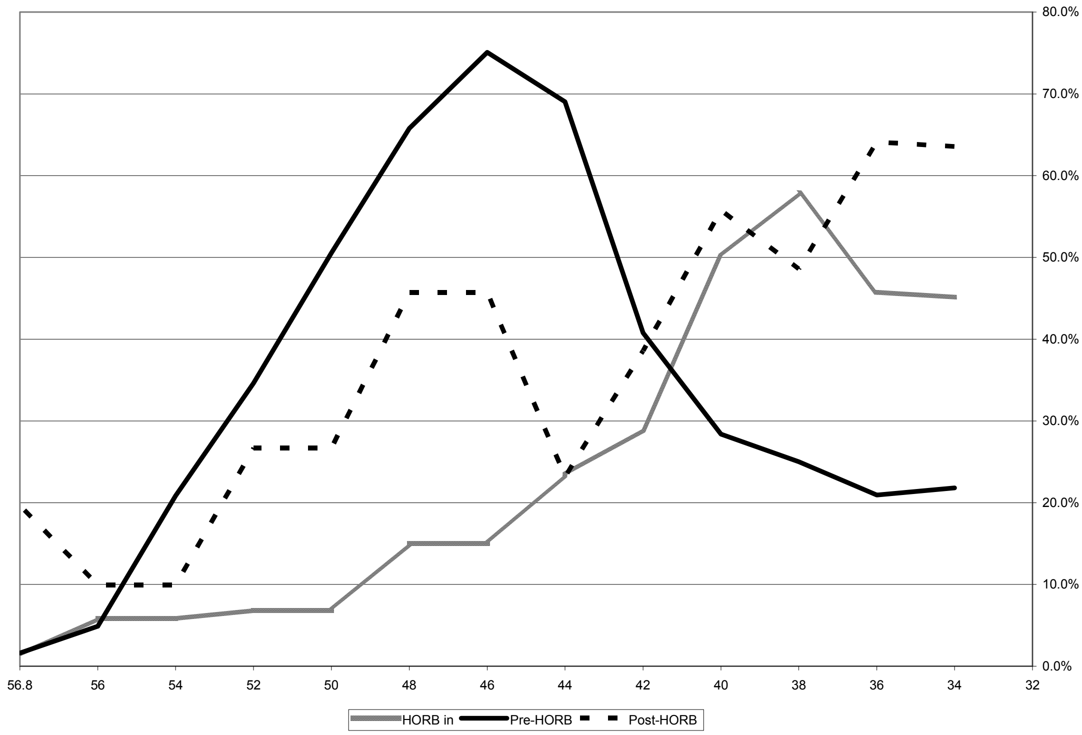

Figure 30: Longitudinal Profiles of Total Zooplankton Biomass for Pre-HORB, HORB Installed, and Post-HORB periods (Biomass was Standardized to Percent of Maximum Sample Biomass. Standardized Biomass Values for Each Sample Location were then Averaged.)

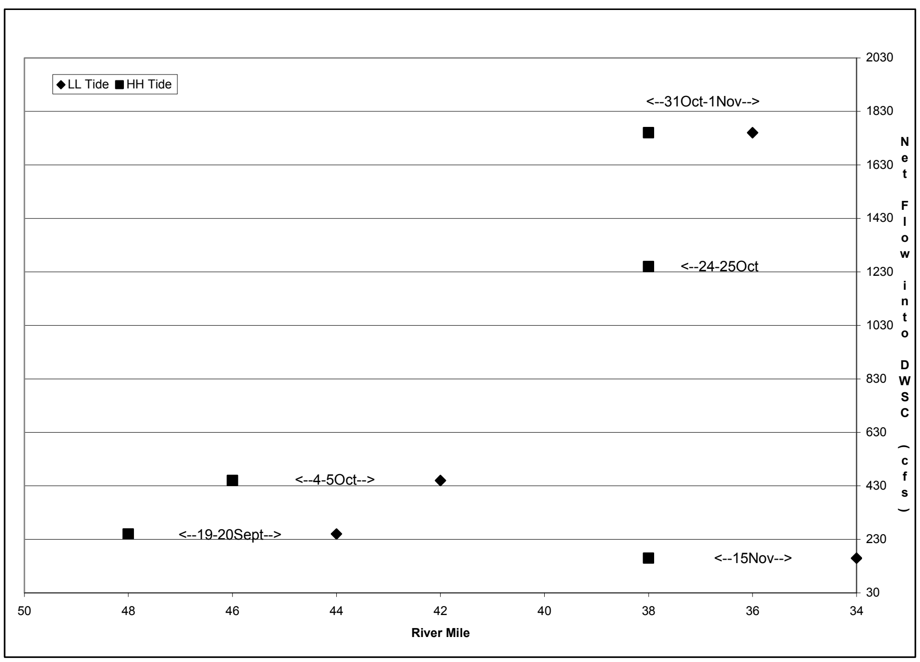

Figure 31: Location of Zooplankton Biomass Peaks during High-High and Low-Low Tides in Relation to Net Flow into the DWSC for Each Sample Period (No Biomass Peak was Discernible for Low-Low Tide on October 24–25, as the Peak was Likely Pushed Downstream of RM 34).

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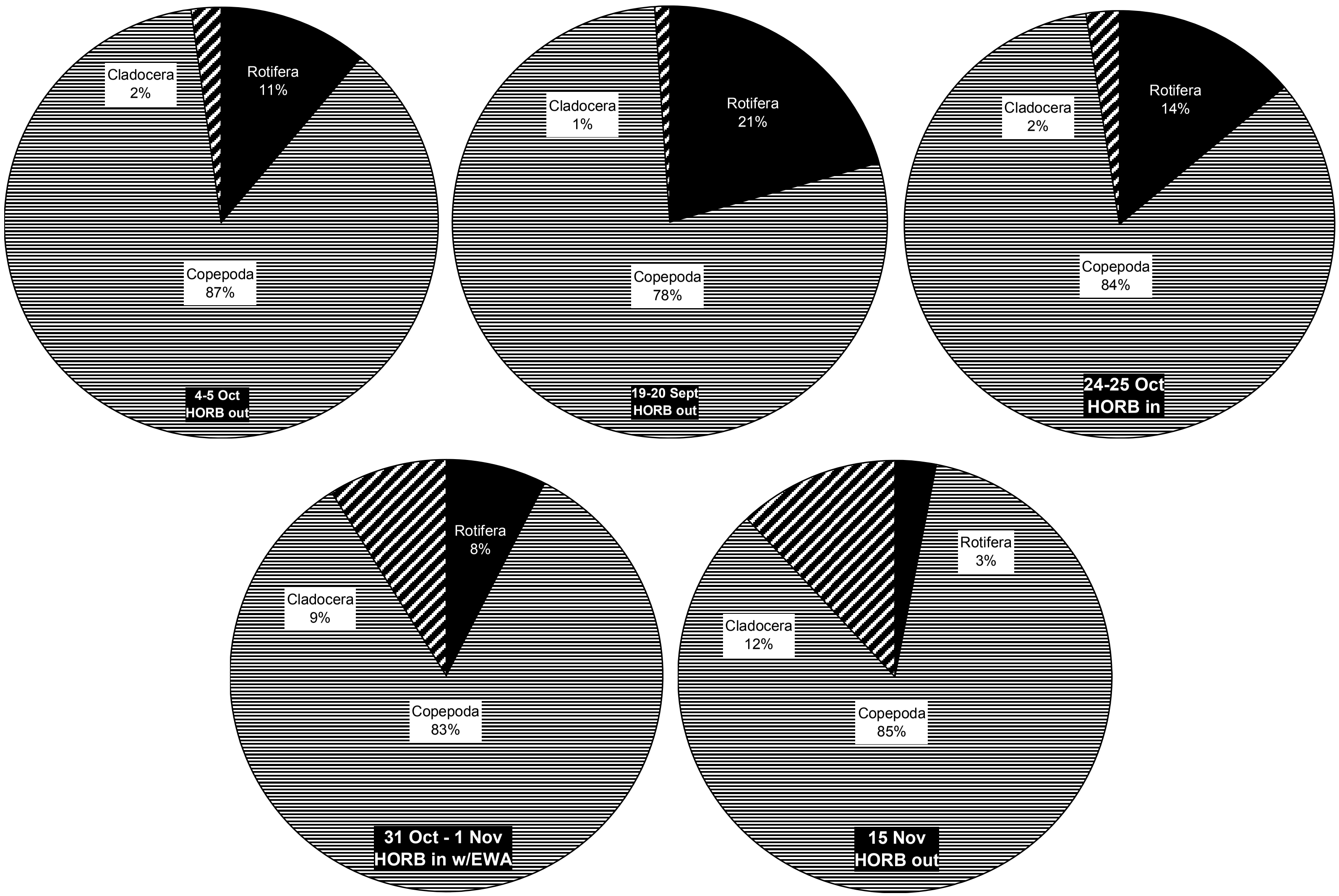

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Figure 32
Changes in Zooplankton Group Representation over the Sample Periods

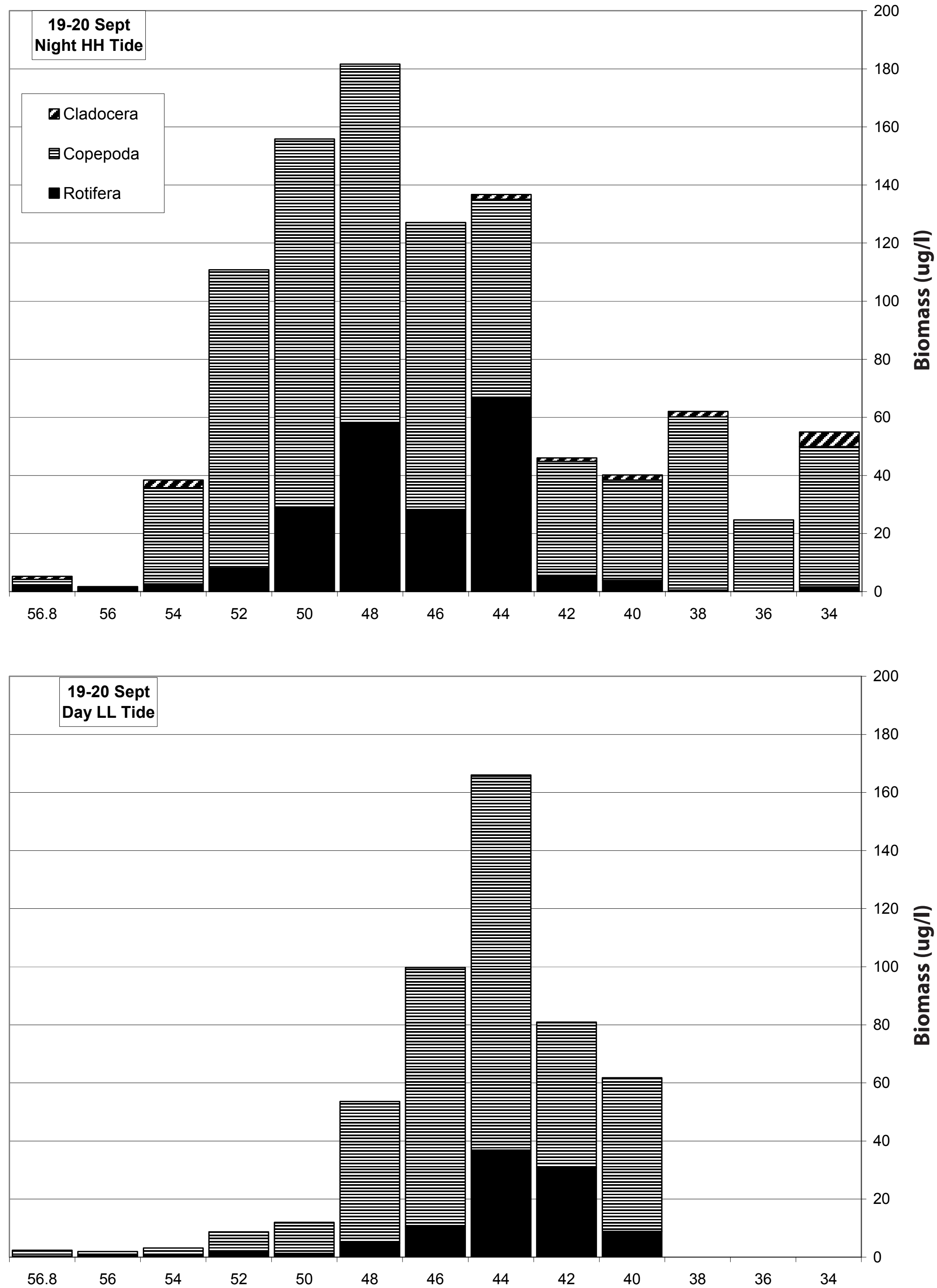

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Figure 33
Longitudinal Profiles of Zooplankton Taxonomic Groups for September 19–20, 2007

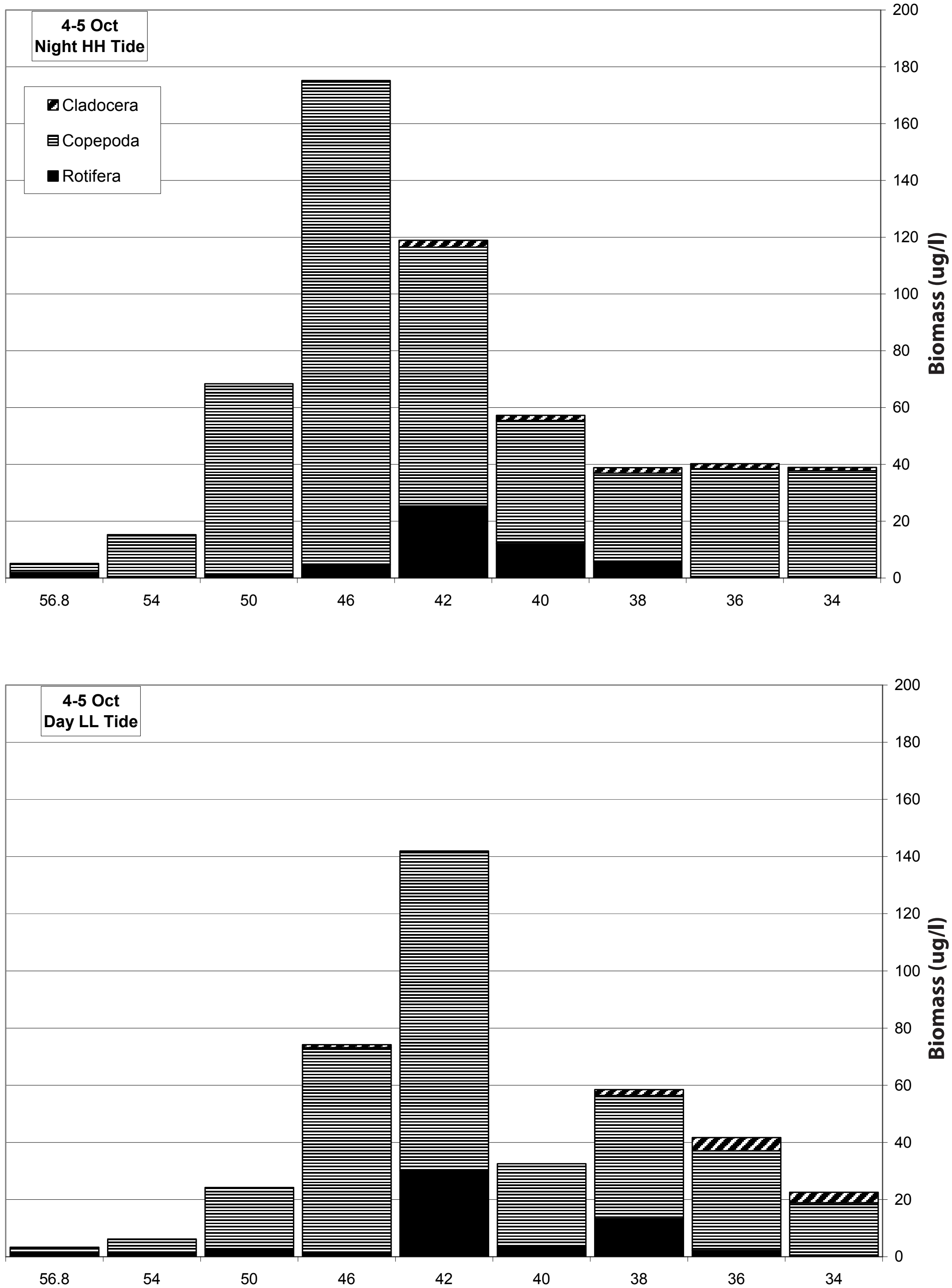

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Figure 34
Longitudinal Profiles of Zooplankton Taxonomic Groups for October 4–5, 2007

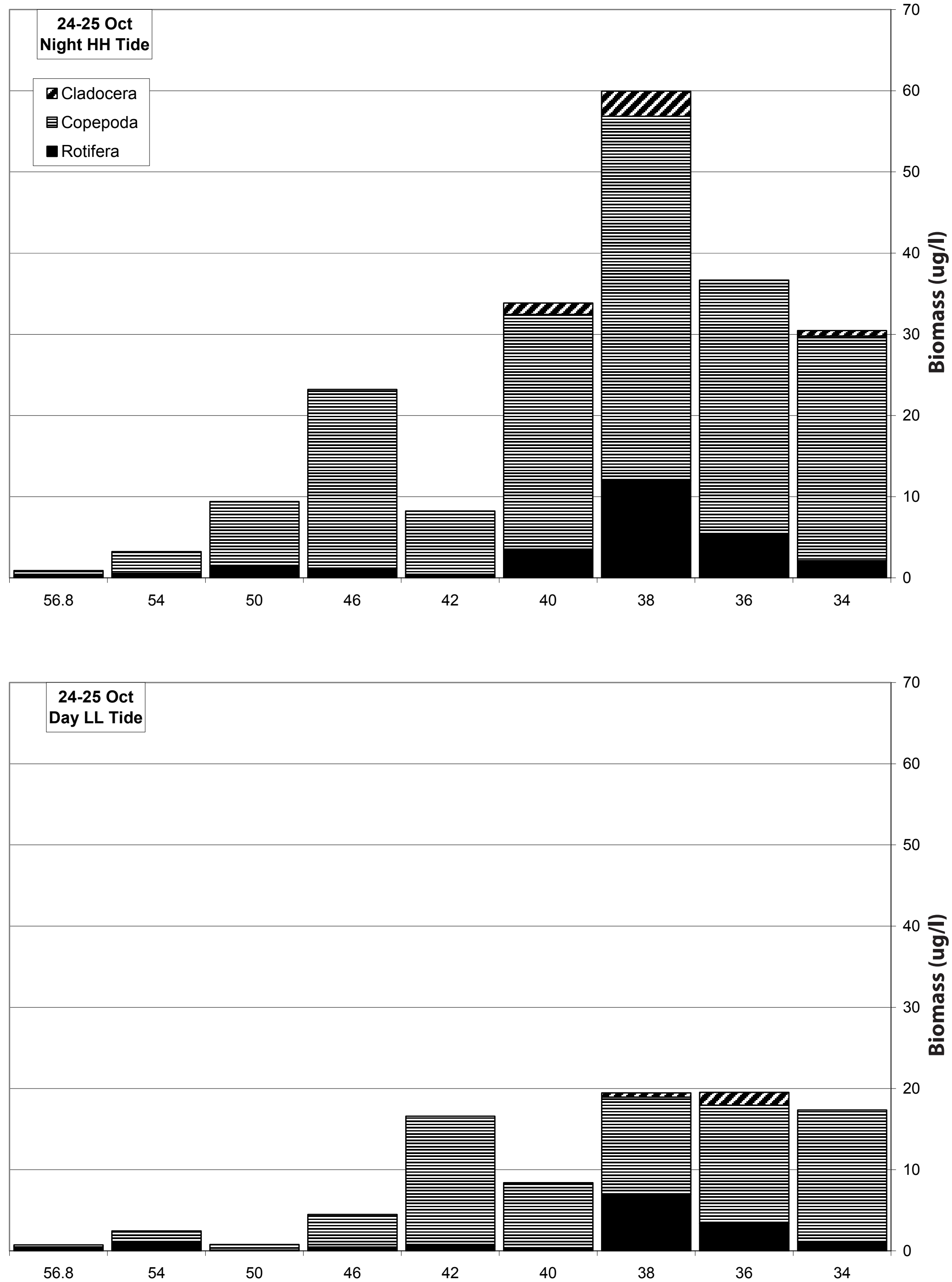

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Figure 35
Longitudinal Profiles of Zooplankton Taxonomic Groups for October 24–25, 2007

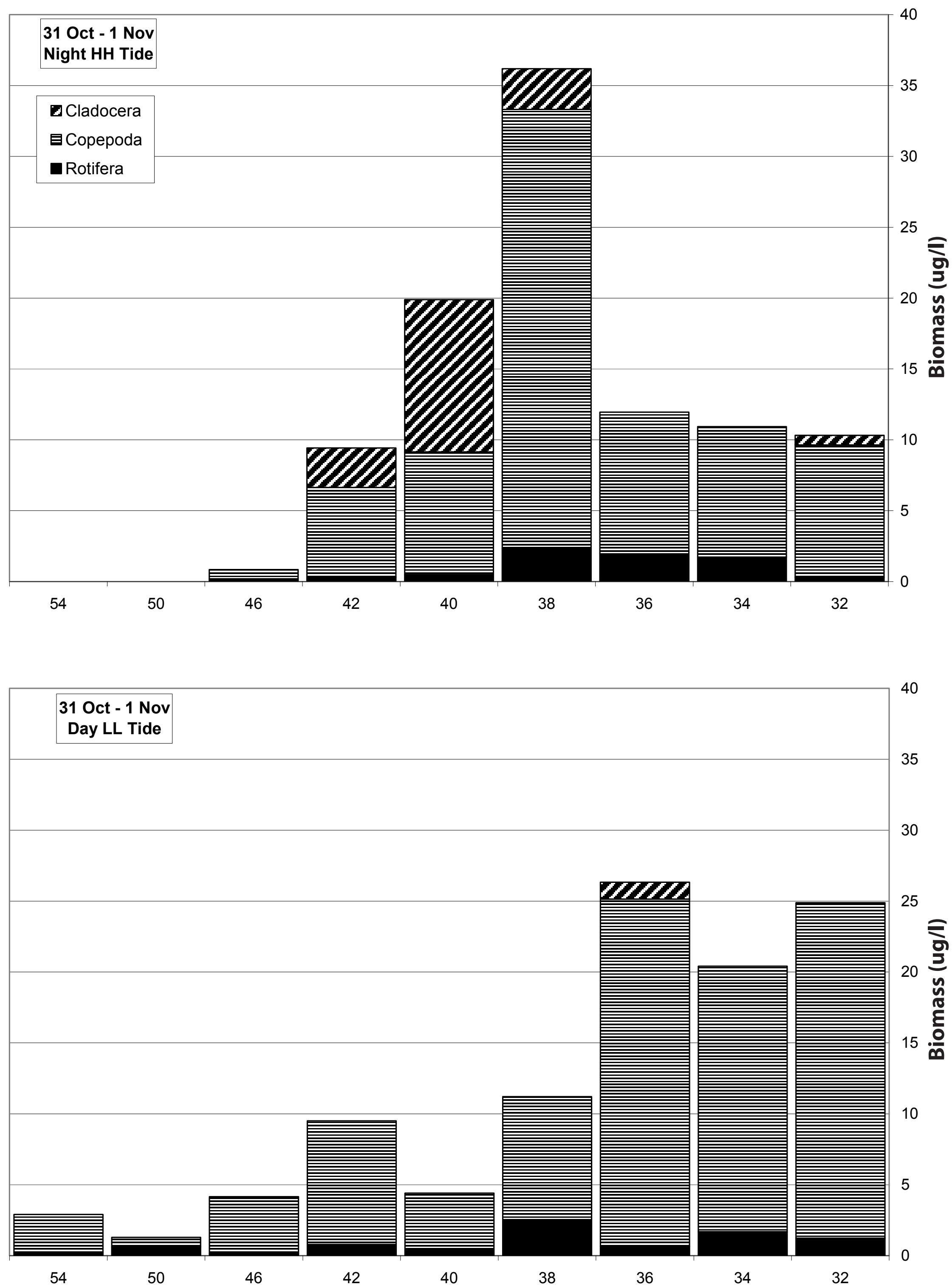

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Figure 36
Longitudinal Profiles of Zooplankton Taxonomic Groups for October 31–November 1, 2007

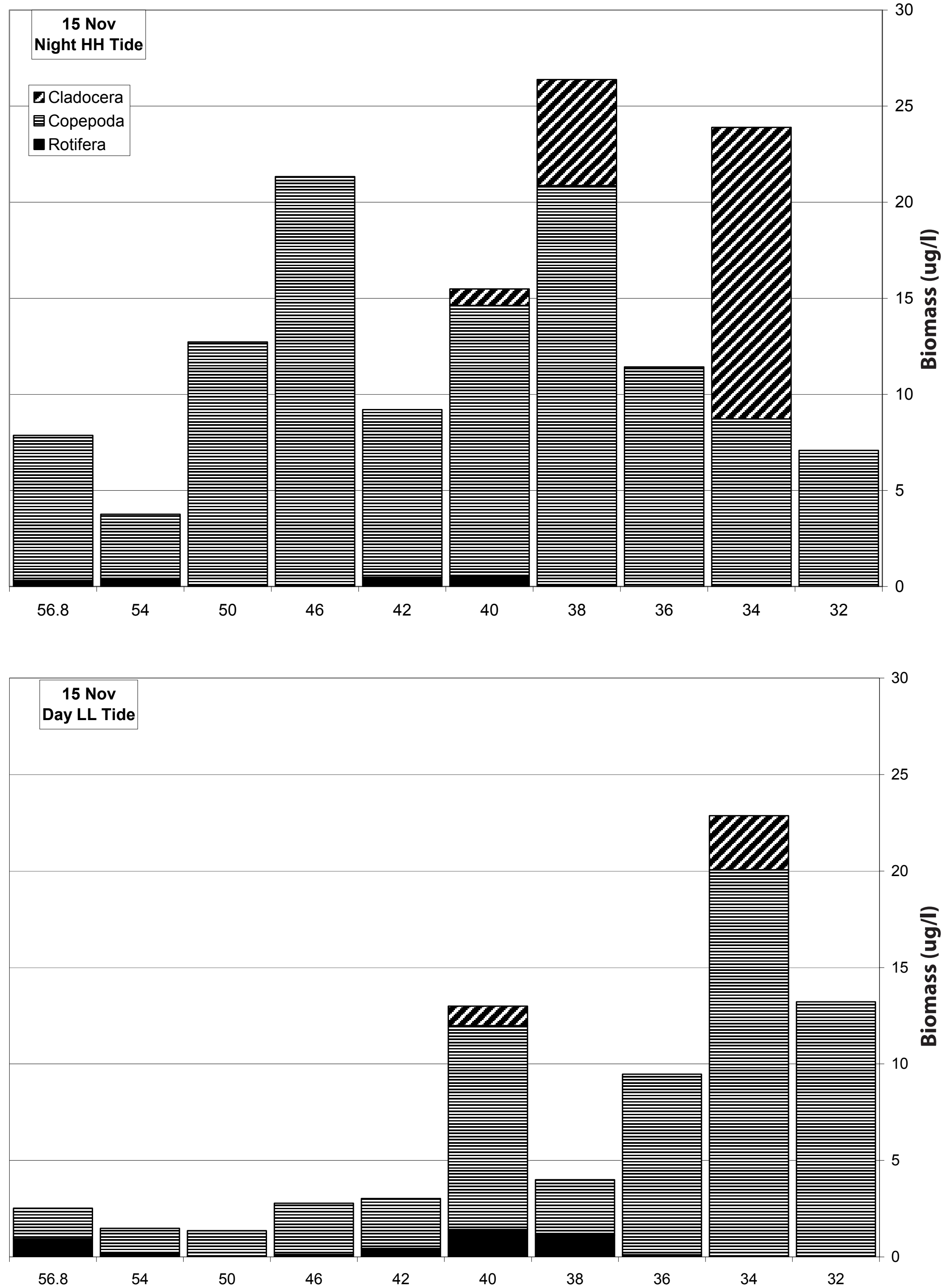

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Figure 37
Longitudinal Profiles of Zooplankton Taxonomic Groups for November 15, 2007